Monitoring of concrete structures using the ultrasonic pulse velocity method

G. Karaiskos [1], A. Deraemaeker [2], D.G. Aggelis [1] and D. Van Hemelrijck [1]

[1] Vrije Universiteit Brussel (VUB), Department of Mechanics of Materials and Constructions (MeMC), Pleinlaan 2, B-1050 Brussels, Belgium

[2] Université Libre de Bruxelles (ULB), Building, Architecture and Town Planning (BATir), 50 Avenue F.D. Roosevelt, CP 194/02, B-1050 Brussels, Belgium

E-mail: gkaraisk@vub.ac.be

Abstract

Concrete is the material most produced by humanity. Its popularity is mainly based on the low production cost and the great structural design flexibility. The operational and the ambient loadings including the environmental effects have a great impact in the performance and overall cost of concrete structures. Thus, the quality control, the structural assessment, the maintenance and the reliable prolongation of the operational service life of the existing concrete structures are turned into a major issue. In the recent years, non-destructive testing (NDT) is becoming increasingly essential for reliable and affordable quality control and integrity assessment not only during the construction of new concrete structures, but also for the existing ones. Choosing the right inspection technique is always followed by a compromise between its performance and cost. In the present paper, the ultrasonic pulse velocity (UPV) method, which is the most well-known and widely-accepted ultrasonic concrete NDT method, is thoroughly reviewed and compared with other well-established NDT approaches. Their principles, inherent limitations and reliability are reviewed. In addition, while the majority of the current UPV techniques are based on the use of piezoelectric transducers held on the surface of the concrete, special attention is paid to the very promising technique using low-cost and aggregate-size piezoelectric transducers embedded in the material. That technique has been evaluated based on a series of parameters, such as the ease of use, cost, reliability and performance.

Keywords: non-destructive testing, ultrasonic pulse velocity, cementitious materials, early age, defect detection and monitoring, embedded transducers.

1. Introduction

Concrete is a highly-complex quasi-brittle heterogeneous and anisotropic composite material that is made by binding aggregates together using cement paste and it is characterized by a low capacity for deformation under tensile stress. The efficiency of the consolidation during the setting and hardening period is crucial for attaining the full potential of a concrete mixture. Although concrete is distinguished by such a high durability and compressive strength, it is vulnerable in a series of operational and ambient degradation factors which can seriously decrease its operational service life. Mechanical loading, harmful chemical reactions and environmental effects can result in the development of harmful tensile stresses in concrete. These tensile stresses all too frequently result in cracking that can adversely affect the performance of concrete [1-3]. In most concrete structures, when they begin to deteriorate, they do so slowly at first and then gradually progress to failure. Figure 1 shows a listing of the most common causes of cracking generation in concrete structures during hydration or in hardened state [4-6]. Thus, planned monitoring, maintenance and damage restoration can reliably extend their operational service life.

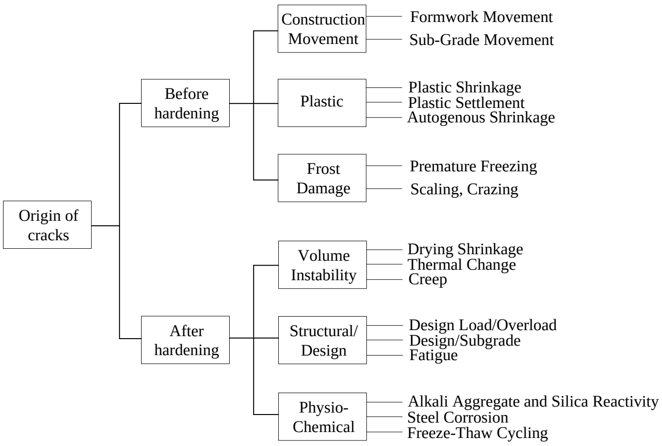

Figure 1. Common causes of cracking generation in concrete structures.

In concrete structures, steel reinforcement is used to counteract the low tensile strength and ductility of concrete as well as to bridge and hold the elements of a concrete structure together. In normal conditions, the concrete covers and protects the steel reinforcement from corrosion. After significant tensile stress is induced in the concrete structure, some cracking is expected. According to the size and position of the developed cracks, these could either be detectable by the naked eye at the surface or could be internal in a non-accessible point of the structure. Except the aesthetic problems caused, concrete cracking results in stiffness loss and corrosion of the steel reinforcement, which are detrimental to the integrity and the operational service life of the structure which are not guaranteed any more. In addition, the operational, inspection and maintenance costs of the concrete structures are highly dependent on the generation and monitoring of the cracks [7, 8].

Depending on the developed damage during testing, concrete testing can be either destructive or non-destructive. Even though destructive testing provides direct, accurate and reliable information about the structural integrity and quality of the concrete, these methods are harmful for a new construction, let alone for a degraded one. For a long period, the common way to inspect and diagnose the concrete facilities with a high precision has been to perform destructive strength testing and material analysis in a few small samples coming from the existing structure. But carrying out concrete infrastructure assessment using destructive testing techniques is not always possible (e.g. non-accessible concrete volume of interest). Additionally, in large-scale concrete facilities such as dams and tunnels, there is a great spatial variability of measurement points and by definition a reliable condition evaluation is extremely costly and time demanding. Conversely, the harmless non-destructive tests can be applied quickly at a relative low cost but they provide indirect information that needs further post-processing.

Since the 1940s, there is a great interest in non-destructive testing (NDT) methods for both early-age and hardened concrete not only in the laboratory but also in-situ and significant advancements have been achieved until today [9]. The in-situ non-destructive evaluation of concrete structures is vital to monitor their soundness and prevent their irreversible damage. The main tasks of NDT methods consist of integrity assessment, defect characterization, and quality control not only in new concrete structures, but also in degraded ones before and after the necessary rehabilitative actions. Some of these most challenging tasks in modern civil engineering are attained with the use of several NDT methods which are currently in use and are mainly based on stress wave propagation, electromagnetic wave propagation, radiation, optics and thermography. The most significant characteristic of these techniques is that they indirectly connect the observed phenomena with the mechanical properties of concrete such as stiffness, elastic modulus or compressive strength, using well-established relationships. Those developed relationships may correlate the compressive strength of the tested concrete and the NDT measurement by testing core samples that have been drilled from areas adjacent to the in-situ test locations. The resulted equation with the confidence limits for the estimated concrete compressive strength is developed through regression analysis. Therefore, in-situ NDT measurements can reduce the number of core samples but cannot eliminate it [10]. During construction and without damaging the structure, whole-scale and cost-efficient reliable NDT tests are achievable, which results can be used for the estimation of the concrete strength, enabling the safe continuity of operations [11-13].

Among these NDT methods, ultrasonic testing plays an important role because of its ease of use at a reasonable cost. Ultrasonic wave-based propagation systems are among the most widely-used NDT methods and they could be divided in two main groups: Through-transmission ultrasonic pulse velocity (UPV) and pulse-echo systems. The early attempts at using pulse-echo equipment were not so promising because of the great heterogeneity of the concrete, but the through-transmission UPV method is still successfully used and continuously developed. Various ultrasonic wave propagation characteristics such as velocity, amplitude, attenuation, frequency and energy can be used to determine the properties, detect the damages and assess their severity as well as feed properly calibrated numerical models in order to estimate the residual service life of the monitored concrete structure. Today, the UPV method gains further ground in the scientific community in the field of structural health monitoring (SHM). In-situ measurements are compared with the reference ones in order to assess the condition of the material. The ratio of those measurements indicates the level of material degradation. While the majority of the current techniques are based on the use of piezoelectric transducers held on the surface of concrete, special attention is paid in the very promising technique using piezoelectric transducers embedded in concrete structures. The results so far show a good agreement with classical ultrasonic tests using external transducers [14, 15].

There is a great need for in-situ testing of concrete as a result of a steadily increasing number of concrete structures showing signs of structural degradation and the infrastructure agencies are shifting efforts from building new concrete structures to assessing and rehabilitating the existing ones. It has become apparent that reliable tools are required for error-free concrete strength and integrity performance evaluation of the existing structures, so that the most cost-effective strategy of rehabilitation can be adopted. The reduction of the inspection cost and risk of unexpected failure using real-time on-line monitoring systems is of utmost importance [11]. In this regard, the principal aim of this paper is to provide an overview and comparative study between the well-established and continuously developed UPV method and the available or recently developed NDT methods in the frame of ease of use, cost, reliability and operational performance.

2. Historical background

Traditionally, the non-destructive quality evaluation and structural integrity of concrete has been performed largely by visual inspection and surface sounding which is referred to striking the surface of the concrete and interpreting the characteristics of the resulting sound. The obvious limitations of visual inspection that only visible macroscopic damages at accessible locations of the structure can be inspected as well as no quantitative information is obtained usually make it an inadequate NDT method [12]. The use of sound techniques in order to assess the integrity of structures is probably as old as human's interest in the structural integrity and failure. The first serious steps toward this direction were taken in 1870s through the work on sound of Lord Rayleigh, 'The Theory of Sound', where the behavior of sound waves in gases, liquids and solids were explained [16]. By transmitting ultrasonic waves through blocks of different materials, it was possible to measure the elastic constant values of them.

In general, ultrasonics is the application of sound waves with a frequency greater than the upper limit of the human hearing range which is approximately 20 kHz. In cementitious materials such as concrete, lower frequency ultrasound can be used to detect flaws and damage. The direct piezoelectric effect, discovered by the brothers Jacques and Pierre Curie in 1880 [17] as well as the reverse piezoelectric effect discovered by Lippmann in 1881 [18] are essential in designing the transducers to generate and receive ultrasonic waves. World War II accelerated the research concerning the NDT methods using ultrasonics technology in concrete. The initial approach of concrete quality assessment (dynamic modulus of elasticity calculation) was achieved by Long et al [19], involving two receivers attached to the concrete. A hammer hit was applied in line with the receivers and a synchronized timer was used to measure the time needed for the generated stress waves to travel from the first to the second receiver. Since the late 1940s, Jones [20] in England (at the Road Research Laboratory (RRL)) and Leslie and Cheesman [21] in Canada (at the Hydro-Electric Power Commission of Ontario (Ontario Hydro)) independently suggested quite similar ultrasonic testers for the NDT quality evaluation of concrete. Jones developed the ultrasonic concrete tester and Leslie and Cheesman developed the soniscope.

The soniscope, was oriented for crack detection and monitoring in dams as well as to determine the dynamic modulus of elasticity of concrete used. It consisted of a piezoelectric transducer capable of transmitting ultrasonic stress waves penetrating up to 15 m. The fundamental measurement of that device was the transit time of the stress wave with an accuracy of 3%, while the amplitude of the received signal was of minor importance because the energy transfer between the transducer and the concrete could not be controlled. Parker [22] reported that the initial use of the soniscope was mainly oriented on measuring the pulse velocity on mass concrete for detecting the damaged areas rather than on the strength assessment. Based only on pulse velocity measurements, the presence of damaged concrete could be easily detected. He also reported an early attempt in order to correlate the pulse velocity and the compressive strength of the concrete. Forty-six different concrete mixtures involving the same aggregates, different type of cement and different admixtures were tested. The results revealed very early the inherent uncertainty in using pulse velocity to directly estimate the concrete strength. In 1967, Whitehurst reported field applications using a soniscope developed in the United States. A rough classification for using pulse velocity as a quality indicator of normal concrete (table 1) was also published [23, 24].

Table 1. Quality classification of normal concrete according to the pulse velocity [24].

Longitudinal pulse velocity (m/s)	Concrete quality
> 4570	excellent
3660 - 4570	generally good
3050 - 3660	questionable
2130 - 3050	generally poor
< 2130	very poor

The ultrasonic concrete tester developed by Jones was mainly focused on testing the quality of concrete pavements [25]. Because of the short path lengths in concrete pavements, the ultrasonic tester operated at a higher frequency than the one used in the soniscope. High resonant frequency transducers (from 60 up to 200 kHz) were developed and used according to the desired penetration and the transit time of the stress wave could be measured within ±2 μs [26]. Additionally, the influence of the water to cement ratio, the aggregate type and content on pulse velocity as well as the relationship between the pulse velocity and compressive strength were also investigated [20].

It was not until 1967 that UPV finally became an official test method in the U.S. [27] and the American Society for Testing and Materials (ASTM) adopted the proposed test method published by Leslie in 1955 [28]. In Europe, the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) published draft recommendations for testing concrete using that method in 1969 [29]. In the same period, researchers from the Netherlands Organization for Applied Scientific Research (TNO) developed a portable and easy to use UPV device. That portable system had a low accuracy, especially in short path lengths measurements, and it also had limited penetrating ability [30]. A similar portable device known as PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester) system was also developed by Elvery [31]. It is obvious that there has been a growing trend for in-situ testing of the concrete structure not only during the construction but also during its whole service life. Failure of reliable concrete strength assessment can lead in tragic construction failure such as the Skyline Plaza collapse in Virginia in 1973 [32] and the cooling tower disaster in Willow Island, West Virginia in 1978 [33]. That disaster highlights the great importance of fresh concrete strength monitoring.

It is interesting to note that since 1980s the digital electronics and computer innovations have positively affected the NDT methods for concrete. The reduction of the inspection costs and the alleviation of unexpected failure started to be the main pillars during the development of real-time monitoring systems. In that direction, many efforts have been made in the recent years in order to develop fully automated SHM systems based on ultrasonic wave propagation for in-situ applications. In the present, a lot of research teams deploy and further develop the UPV method using mainly surface attached transducers [34-36]. This method can be used in concrete structures not only for defect detection, but also for hydration monitoring. The UPV method is a real NDT technique as the high frequency wave propagation through the concrete does not have any side effect on the integrity of the tested concrete structure.

3. The ultrasonic pulse velocity method

3.1. Working principle

When pressure or impact is applied suddenly on the surface of a solid, ultrasonic stress waves are generated. The generated disturbance propagates through the solid in a manner analogous to the sound traveling through the air. Several parameters, such as the type and density of reinforcement, the material composition, the severity and location of internal defects, the mechanical properties and the surface conditions influence the wave propagation in concrete. Based on the way the particles oscillate, various modes of ultrasonic waves can propagate in solids. The longitudinal (or compressional), shear (or transverse) and surface (or Rayleigh) waves are the most widely used modes of propagation in ultrasonic testing. The longitudinal waves are the fastest waves and the surface waves are the slowest ones. In longitudinal waves, the particles oscillate in a direction which is parallel to the direction of wave propagation. In shear waves, the particles oscillate in a direction which is perpendicular to the direction of wave propagation. The Rayleigh waves propagate along the surface of the solid and the particles motion is elliptical, with the vertical component greater than the horizontal one [37].

The UPV method is the most widely-used and accepted concrete NDT method as it can be used in determining material properties, detecting defects as well as assessing structural integrity. It uses the stress wave propagation and it is based on the measurement of the transit time T which is the interval between the onset time of the input pulse of ultrasonic longitudinal wave and the onset time of the received stress wave over a known path length L of the tested structure. The testing system typically consists of a high-voltage pulser, an amplifier, the main control unit which includes a synchronized electronic timer and a pair of similar piezoelectric transducers (i.e. transmitter and receiver). The piezoelectric transducers can be used both as actuators (i.e. transmitters) to generate ultrasonic stress waves and as sensors (i.e. receivers) to detect the propagating waves. Typical transducers generate the ultrasonic stress waves by exciting a piezoelectric disk in an average frequency range, for concrete applications, from 20 kHz to 300 kHz. The wavelength of the stress wave used should be properly adapted to each testing task. Too high wavelength omits small defects resulting in a signal with great penetration depth and too small wavelength provokes serious attenuation in the transmitted wave resulting in a signal with great sensitivity in various sizes of defects but with a small penetration depth. The main control unit of the system should have a very high time measurement resolution of at least 1 μs. Initially, a short-duration low-amplitude voltage pulse is generated in the main control unit and it is amplified (up to 1000 V) using the high-voltage pulser. Then, it is introduced into the transmitter and a triggering pulse is produced by the transmitter in order to switch on a synchronized electronic timer which starts measuring the transit time T. The high-amplitude spike-shape signal excites the transmitter to vibrate at its resonant frequency and this vibration excites the material through contact with a wide range of ultrasonic frequencies and generates stress waves. The generated stress waves propagate through the material and they are detected by the receiver, which is also held in contact with an opposite surface of the tested specimen at a distance L from the transmitter. Then another triggering pulse is produced by the receiver which triggers the electronic timer to switch off. The signal acquired by the receiver is conditioned by an amplifier before being stored in the main control unit of the system [27].

The transmitted ultrasonic stress waves undergo partial signal loss and scattering noise due to reflection, refraction and mode conversion caused by aggregates, pores, steel reinforcement and any defect found along the travel path in the concrete specimen (figure 2). The stress waves are mainly reflected at the interfaces of the tested concrete specimen where the acoustic impedance, defined by the density and wave speed (equation 1) of the material is modified.

$$z = \rho c \tag{1}$$

where ρ is the density and c is the wave speed of the material. Based on the measured transit time T and the path length L, the velocity of the transmitted ultrasonic stress waves (in km/s or m/s), which is the most easily evaluated parameter, is calculated by simply dividing L by T and is correlated to the condition of the concrete under test.

$$V = \frac{L}{T} \tag{2}$$

The ultrasonic pulse velocity of longitudinal stress waves in infinite concrete specimen is directly related to the dynamic modulus of elasticity, Poisson's ratio and mass density through the following equation [38]

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{3}$$

where E is the dynamic modulus of elasticity, μ is the dynamic Poisson's ratio and ρ is the mass density. That direct dependence between the properties of concrete and the resultant UPV permits deductive conclusions about the characteristics of the concrete by monitoring the propagation of ultrasonic stress waves. Because the wave propagation depends on the material properties of the tested specimen, many efforts have been made to link the compressive strength with the velocity V of the transmitted ultrasonic stress waves. To be more specific and according to the above equation, the pulse velocity varies proportionally to the square root of the elastic modulus which is frequently expressed in terms of compressive strength. Thus, many researchers have tried to provide an estimation of the concrete compressive strength through the pulse velocity measurements, but over a wide range of maturity, the relationship between them is highly nonlinear [11, 12].

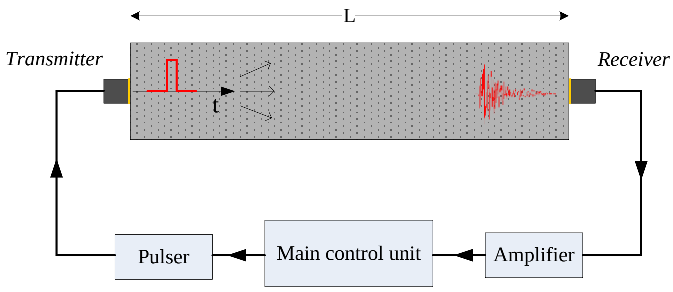

Figure 2. Schematic of apparatus of the UPV test system.

Except the velocity V, the attenuation a of the ultrasonic stress wave (in dB/m) is theoretically possible to be deduced from the decrease of the amplitude A_1 and A_2 of the received signal for two different paths with lengths L_1 and L_2 respectively. This is a measure of the intrinsic damping of the monitored material and it is empirically related with its strength [39].

$$a = \frac{20}{L_2 - L_1} \log\left(\frac{A_1}{A_2}\right) \quad (4)$$

The quality of the received signal depends on the accuracy of the measurement of the distance L and the coupling of the transducers to the concrete surfaces. Special care should be taken to obtain good coupling between the transducers and the concrete at each testing point. In order to maximize the coupling and eliminate the presence of air pockets between the transducer and the concrete surface, sufficient pressure to the transducers must be applied and an appropriate coupling agent such as gel, vaseline, honey or grease must be also applied on their interface with the concrete surfaces (figure 2). Today, new air coupling transducers with specific amplifiers avoiding any contact with the tested material are under development. These new transducers get rid of the problem of coupling between the transducer face and the tested concrete. [12, 40, 41].

By conducting tests at various points on a structure, the quality and uniformity of concrete are assessed. The locally increased transit time T of the transmitting pulse is an indicator of loss of soundness possibly due to low-stiffness material, cracking, honeycombing, voids, frozen concrete, delamination and other non-homogeneous areas as the ones resulting from various degrading mechanical, chemical, thermal and environmental loadings. The pulse may be diffracted due to the discontinuities thus increasing both the transit time T and the path length L. It is possible to assess the uniformity of the concrete structure when a grid of UPV measurements is made over the region of interest (figure 3). Thus, the different zones (damaged or not) are localized in the monitored structure, which allows the operator to be further focused on the most suspect ones where further complementary tests could be made, which obviously increase the total time and cost of the project. While the UPV method can be successfully used to mainly detect defects in concrete, yet it cannot identify their nature. Additionally, not only damage detection is feasible, but also its progress and possible rehabilitation may also be monitored [12, 42-45].

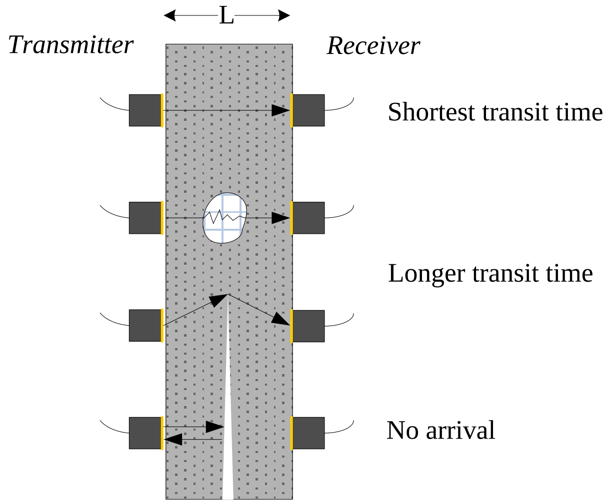

Figure 3. UPV testing through different material conditions.

3.2. Transducers arrangement

According to the amount of energy propagated from transmitter to receiver, there are mainly three different transducer arrangements. The maximum energy is propagated by placing the transducers on opposite faces (direct transmission) in the concrete structure under test. Whenever two opposite faces are not available, then the transducers are placed either on adjacent faces (semi-direct transmission) or on the same face (indirect or surface transmission) (figure 4).

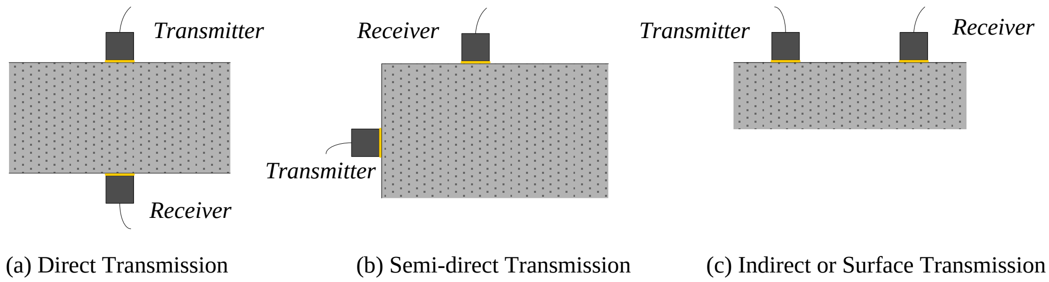

Figure 4. Possible arrangements of transducers.

Direct transmission is the most sensitive arrangement and indirect transmission is the least sensitive one. For each of the available arrangements of transducers, there is a respective way how the path length L is measured. For direct transmission, the measured path length L is the distance between the transducers and for semi-direct transmission it is generally acceptable to take the path length as the distance measured from centre to centre of the transducers faces. Various standards are available for measuring the direct transmission pulse velocity in concrete. Additionally, for the indirect or surface transmission, the path length is correlated to a series of measurements made with the transducers at different distances apart [25, 46-48]. A discrepancy of about 5% to 20% between the pulse velocities of direct and indirect transmission is due to the increased porosity and damage accumulation of the surface layer of concrete [9, 47, 49]. The indirect arrangement of transducers has been also suggested when the quality of the surface concrete relative to the overall quality is of interest, such as in case of harmful incidents like fire [50-52] and frost [53, 54]. Combination of several wave paths in the direct or indirect transmission mode can lead to the visualization of the interior damage pattern of the structure through tomography algorithms [55-57].

Except the UPV method and the measurement of the transit time T of the stress wave, the amplitude of the surface Rayleigh wave that survives beneath the surface defects, such as cracking and delamination, could be also an alternative option for the surface evaluation of concrete structures. Actually, the spectral analysis of surface waves analyzes the propagation mode of the dispersive waves just below the surface, which allows the defect assessment. Typically, the penetration depth of the surface waves is considered to be close to their wavelength. Focused on the surface waves, the structural integrity of the upper layer of the concrete can be assessed, which is essential for the layered concrete structures such as pavements, tunnel liners, bridge deck panels and dams. In addition, the surface waves are considered 2D waves so their energy attenuation and dispersion are not valued as high as the ones found in the 3D waves such as the longitudinal and shear waves. As a result the surface waves can be used to effectively assess concrete samples over larger distances than using longitudinal or shear waves [12, 58, 59].

3.3. Correlation between UPV and compressive strength of concrete

There is often a need to estimate the compressive strength of concrete in existing infrastructure due to various reasons such as change in the use or after a structural failure and among the earliest applications of ultrasound techniques in concrete is the effort to directly correlate the UPV to compressive strength [36, 60]. According to the equation (3), the UPV is dependent on the elastic modulus and the density. The elastic modulus and the compressive strength of concrete increase with maturity. Thus, the pulse velocity may provide an estimation of the compressive strength of the tested concrete, even though as concrete matures these two properties increase at different rates. [11, 12].

Popovics [61] stated that a lot of parameters that influence the compressive strength of concrete also influence the UPV, although not necessarily in the same manner or to the same degree. To be more specific, the elastic modulus and density are related to the type and amount of aggregates, the water-to-cement ratio, the curing conditions, the cement type and the age of the concrete. Conversely, the compressive strength is more related to the water-to-cement ratio than to the type and amount of aggregates used. Various experiments have been carried out to establish mathematical models for predicting the UPV based on water to cement ratio, aggregate content and curing time [62]. It has been proved that concrete mixes with lower water-to-cement ratio produce concrete with higher values of UPV and compressive strength and that could be attributed to the higher amount of solids in those mixes [63-65]. The influence of aggregate gradation, the type of cement, the concrete, the ambient temperature, the water to cement ratio and the curing conditions on the relationship of compressive strength and UPV has also been studied. In general, the larger the aggregate size used in the concrete mix, the higher the measured UPV. On the contrary, the compressive strength is increased as the maximum aggregate size is decreased. Additionally, UPV is increased as curing time increased along with compressive strength [64, 66]. Thus, correlations between the UPV and strength of concrete are not general and there is no single relationship between these two quantities but this has to be established for the specific concrete mix [46, 48, 67, 68]. As long as a calibration curve exists for each assessed concrete mix, the UPV might be used for the estimation of the compressive strength [69]. In addition, the presence of moisture may increase the pulse velocity up to 5% [34] but, the moisture also affects the compressive strength negatively [70]. A high volume of moisture content may be the sign of concrete degradation which enables damage mechanisms. Moreover, the presence of steel reinforcement aligned with the wave path significantly increases the measured pulse velocity and may overshadow changes due to compressive strength. Measurements close to steel reinforcement parallel to the direction of pulse propagation should be avoided [12, 48, 71]. When this is unavoidable, they must then be corrected by correction factors [46, 72]. The curing process also affects the correlation between the pulse velocity and the compressive strength of the concrete, especially when accelerated methods are used [73, 74]. Concerning the curing conditions, no remarkable differences between results coming from concrete samples subjected to membrane curing (in order to prevent moisture loss) and water curing [75] have been found, but for a saturated concrete, the UPV is higher than for a concrete that hardens in air. Additionally, it has been proved that self-compacted concrete cubes have given better UPV results after curing in water compared with cubes cured in membrane or in air [76]. Subsequent results [77] reconfirm that the highest compressive strength and UPV values are obtained from concrete subjected to water curing followed by the membrane and air curing, regardless of the type of concrete tested. In general terms, all the monitored concrete affects the transit time T and the test results are relatively insensitive to its normal inherent heterogeneity, showing a high repeatability [11].

3.4. On the use of alternative concrete NDT methods and their combinations

An alternative method to use the ultrasonic stress waves for assessing the integrity and quality of the concrete structure, without having access to opposite or adjacent faces of the concrete specimen, is to use the pulse-echo method. Stress pulses are transmitted and received using single- and multi-point piezoelectric transducers. Using the measured transit time T of the ultrasonic stress waves which are reflected or backscattered at interval interfaces, flaws or objects (steel reinforcement) and the pulse velocity V which is known from calibration measurements, the depth of those interfaces, flaws or objects can be easily deduced if the piezoelectric transducers are sufficiently focused and a good coupling between the transducers and the concrete is achieved. Due to high heterogeneity of the concrete, it may be difficult to distinguish actual flaws. It is obvious that the pulse-echo technique is a narrow-field NDT method. Thus, in case of using it, in monitoring large-scale concrete structures, then the time and the cost needed are increased. The use of high frequency stress waves is prevented when large-size aggregate is used in the concrete mix and the low-frequency stress waves produce disturbing surface waves which are detected by the receiver(s) of the system. Thus, the reliability of the technique is limited [12, 41, 78].

Except the pulse-echo method and without using its bulky transducers, the impact-echo method could alternatively be used to identify the presence of defects in the concrete structures which are accessible only from one side. The method is based on the use of transient stress waves by simply monitoring the arrival time of reflected stress waves caused by a short-duration mechanical impact applied to the concrete surface. It is able to detect the depth of the reflecting interface which possibly comes from internal cracking, delamination, honeycombing and voids. Not only special attention must be paid to ensure good coupling between the receiving transducer and the concrete surface, but it is also imperative that the transducer tip should be located close to the impact point. Through the impact-echo method, only the structure directly below the excitation point is assessed which makes it a quite costly and time consuming NDT method in order to inspect large volume concrete structures. Thus it is mainly focused on a small volume of the material and for reaching safe conclusions, a series of measurements is suggested on a predefined grid of positions on the tested concrete structure. The development of a standard test method for flaw detection using impact-echo method is difficult because of the many variables and conditions that may be encountered in field-testing [12, 41, 78-80].

In case of a larger volume of the structure needs to be tested, the impulse-response method can be used, but it cannot exactly locate the position of a defect. It is an affordable way to quickly scan the whole concrete specimen and in case of suspicious results obtained, then detailed investigation through more sensitive NDT methods is needed. The impulse-response method is quite similar to the impact-echo method except that the impact excitation force is measured and more complex post-processing of the received results is needed, as it is based on the analysis of structural mode shapes of the tested element [12, 78].

In contrast to the aforementioned stress-wave based NDT flaw detection methods, where a pulse is sent into the tested concrete specimen, the acoustic emission (AE) NDT method waits for the emission of an elastic stress wave due to a defect generation or propagation. Even if AE can be successfully applied in various defects detection and localization, it cannot provide quantitative assessment concerning the damage level of the monitored concrete structure. In addition, due to the great sensitivity of the AE method, the extraction of the useful information from noisy in-situ applications is not easy and taking into account that the tested structure should be under loading during the test, in order to trigger the emission of the stress waves, that makes it a challenging procedure [81, 82].

When access is limited to only one side of the tested concrete specimen and any contact with the structure is forbidden, then electromagnetic waves can be transmitted by an antenna placed at a distance from the concrete surface. A short-duration electromagnetic pulse is initially introduced into the concrete and part of it is reflected back to the antenna due to the presence of internal interfaces (defects or embedded objects). The ground penetrating radar (GPR) or short-pulse penetrating radar method is mainly used in monitoring layered concrete structures such as highways, bridge decks and pavements. In addition, this method shows potential application in monitoring the cement hydration or the strength development in concrete but the interpretation of the received results is the most challenging task [10, 41, 83, 84]. The sophisticated nuclear methods, such as the radiometry, radiography and neutron-gamma techniques, can be useful and accurate NDT diagnostic tools. Due to the high costs and the complex technology involved as well as the limited active penetration depth in the concrete, it is not widely used in the laboratory, let alone in the field. High-energy electromagnetic radiation is directly emitted to the tested concrete and the transmitted radiation received provides the useful information concerning the physical characteristics and structural integrity of fresh or hardened concrete specimens [10, 12, 85].

Another single-side concrete NDT monitoring method which is designed for wide-field, quick, contactless and affordable assessment of the structural integrity of the tested concrete specimen is the infrared thermography. A high-resolution infrared optical sensor located at a certain distance from the surface under investigation can scan the concrete structure and the possible defects are localized due to the differences of the received thermal radiation. The choice of the sensor's distance from the concrete surface results in a compromise between the spatial resolution and the size of the observed area. Although the dimensions of a defect can be assessed, the depth of it in the tested concrete specimen cannot be determined. Using more sensitive NDT methods, such as one of the available stress-wave propagation based methods, the defect can be localized. In addition, in case of in-situ applications, the influence of ambient conditions should be seriously considered and the tests should be done either early in the morning or late in the afternoon, when there are the highest temperature differences between the damaged and undamaged areas of the monitored structure [86-88].

Finally, the rebound (Schmidt) hammer test consists in a combination of impact loading and stress wave propagation. It is a simple, quick and affordable NDT method for assessing the integrity of concrete structural members as well as for comparing the relative compressive strength at different locations in a concrete structure. Part of the energy generated by the interaction of the probe with the surface of the tested concrete is absorbed as mechanical friction in the instrument and another part is absorbed by the material. The greater the amount of absorbed energy by the concrete, the lower the measured rebound hammer number. The energy absorbed by the concrete is related to the strength and stiffness of the material. There is not any simple and direct unique relationship between rebound number and concrete strength. A correlation should be developed using the same concrete as the one used in the field. In addition, a low-strength and low-stiffness concrete absorbs more energy than a high-strength and high-stiffness one, thus resulting in a lower rebound number. It is possible for two different concrete mixtures to have the same strength but different stiffness, thus resulting in different rebound numbers. Additionally, the rebound hammer is a narrow-field concrete NDT method and therefore the test is sensitive mainly in the near-surface layer of the tested material. Special attention must be paid to specific factors that may affect the integrity of the surface layer of concrete such as carbonation, moisture and chemical degradation. Costly and time-consuming surface treatment (grinding) is necessary either to uncover concrete that really represents the internal concrete of the infrastructure, or to smooth the possibly rough surface of the tested concrete specimen. The test performance is also greatly affected if the probe is impacted over an aggregate particle or reinforcement bar resulting in a great rebound number. On the contrary, if the probe is impacted over an air pocket, a low rebound number will be received. Thus, multiple measurements is suggested in each test area of the monitored structure and each measurement spot should be at least 25 mm away from the previous one. Then, the average value of the accepted collected rebound numbers is used for further post-processing [10, 11, 41, 68, 89, 90].

In order to increase the reliability and precision of the quality evaluation and compressive strength estimation of concrete, combined NDT methods have been proposed since 1960s [91, 92]. Combining the results acquired from more than two NDT methods, a multivariate correlation can be provided for a better estimation in the compressive strength calculation. As a proof of concept, the SonReb method is the most commonly used NDT combination used and it consists in the combined use of UPV and rebound number for better assessing the concrete strength [93-95]. However, the UPV and rebound hammer are influenced in different ways by the same environmental factors, such as moisture. An increase in moisture increases the P-wave velocity but decreases the rebound number. Thus, the combined use of those NDT methods cancels the moisture effect and the accuracy of the estimated compressive strength is improved [96]. In any case, because of the wide range of concrete mixes and the influence of a few uncontrolled parameters during hydration and in hardened state of concrete, there is not any universal multivariate relationship that would directly link the compressive strength of concrete and the received NDT measurements [97]. In addition, combining more than two

NDT monitoring techniques and using multivariate analysis on the received results, significant improvements on structural integrity and compressive strength assessment of the tested structure may still be achieved. However, the extra manpower and cost seems to be prohibitive and in most cases a combination of two NDT methods is used.

3.5. Early-age monitoring of cementitious materials

In addition to the hardened concrete assessment, the UPV method can also successfully monitor the setting and hardening process of fresh cementitious materials. Here, changes in pulse velocity measurements are associated with physical changes which determine the microstructure of the cement paste. Monitoring the hydration process of the fresh concrete, operations that require the specific strength (i.e. post-tensioning applications) of the concrete and the removal of formwork could be carried out as safely as is possible [96]. Until now, the conventional methods to determine the initial setting mainly rely on standard tests like the Vicat needle test [99] for cement paste and the penetration resistance test [98] for mortar. Both methods cannot monitor the hydration continuously and they are not repeatable at the same location due to their destructive nature. Additionally, these methods are not applicable to concrete due to the presence of aggregates [14, 101].

Initially, the hydration of oil well cement slurries using the UPV method was studied. It was observed that the evolution of UPV consisted of three main phases (figure 5) during the transition from the fluid state to the solid state. In the first phase, the UPV is very low and constant and is followed by the second phase where the UPV is rapidly increasing. Finally, in the third phase, the UPV is very slowly increasing and is almost stable. Later on, similar patterns have been found in testing cement paste, mortar and concrete [14, 101-105].

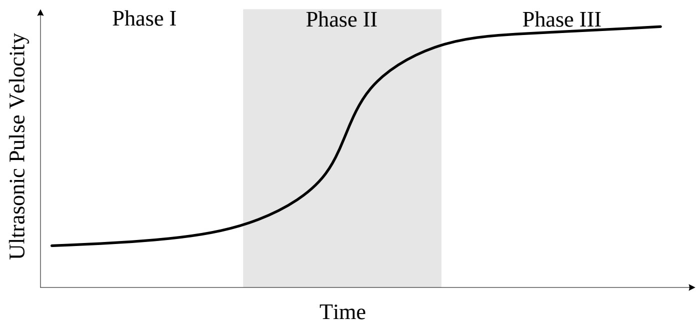

Figure 5. Schematic representation of UPV evolution as a function of time in cementitious materials.

In phase I, the cement paste has not set yet and the UPV is dominated by water, air bubbles and aggregates as revealed by detailed dispersion studies. Indeed by applying wave packets of different frequencies, resonance peaks in phase velocity and attenuation curves are appeared [106, 107]. Scattering on air bubbles seem to govern the behavior at low frequencies (below 200 kHz) while for higher frequencies, the content and size of aggregates are more influential. It is noted, that after hardening the wave behavior of concrete becomes much less dispersive, but still considerable changes may result by application of different frequencies in the range 20 kHz to 200 kHz [108, 109]. This phase is more related to the dissolution and dormant stages of cement hydration. Sayers and Dahlin [110] considered the cement paste in this period as a liquid with uniformly dispersed solid particles. The signal is difficult to measure at very early ages as it tends to be dominated by noise and the UPV values are very close that of water. Starting the phase II and after the dormant period, there is a minimum level of hydration and the air pockets are decreased. The sharp increase of UPV corresponds to the rapid development of hydration products. A drastic increase of the UPV governs that phase and the main transformation from the liquid to the solid phase takes place. Finally, in phase III, the rate of growth of hydration products slows down. There is a slow increase of the UPV and the final stiffness is approached [14, 63, 104, 111, 112].

In most of that research, commercial piezoelectric transducers were placed on the opposite surfaces of a foam rubber or plexiglas made containers where the cementitious material was cast. Due to the shrinkage of the material, it was difficult to keep a stable coupling and the possible shrinkage of the material might seriously affect the quality of the measurement. It is obvious that this method is not suggested as the most appropriate for in-situ measurement because of its requirement of accessing two sides of cast members [113].

Recently, in addition to mortar and concrete, the performance of a series of cementitious composites structural materials has been tested using the UPV method. An efficient way to solve the serious disposal problem of waste automotive tires is to crumb them into small pieces and use them as a substitute of fine aggregates in concrete production. A sustainable construction material called ‘rubbercrete’ is generated which helps to preserve valuable natural resources and to maintain the ecological balance. Various mixtures with different water to cement ratio and crumb rubber content percentages has been tested in both fresh and hardened states. The UPV of the rubbercrete decreases with an increase in the percentage of the crumb rubber content and decreases with an increase in the water to cement ratio. The results also revealed that the UPV increases as the curing age increases [114]. Additionally, shotcrete is the sprayed concrete (or sometimes mortar) especially used for concreting in difficult locations. Its main requirements are adequate adhesion to various substrates and high early strength preventing fallout of fresh material from walls and overheads. For that purpose, a new generation of alkali-free accelerators has been used but they significantly change the microstructure development during the setting and hardening period. De Belie et al in 2005 [115] revealed that the UPV appears to be clearly sensitive to the effect of cement type, accelerator type and dosage on the setting behavior of shotcrete.

3.6. UPV using embedded transducers

Until now, the conventional UPV method is based on the use of external piezoelectric transducers and the quality of the received signal depends on the coupling of the transducers to the cementitious material surface using special agents in such a way to eliminate the presence of air pockets between the transducers and the material. Sometimes, the surface preparation is necessary to maintain a good acoustic contact and that makes difficult to keep stable coupling in ultrasonic measurement. In reality, the contact conditions between the transducers and the tested material are not fully repeatable. Additionally, for all the possible arrangements of transducers (figure 4), at least one of the surfaces of the concrete structure under test should be accessible by the specialized staff. Nevertheless, the majority of structures in the field that need inspection are in service so it will also have an extra cost for the removal of any type of cover and temporarily stopping their operation. Access to opposite faces of in-situ structures may not be readily available and the indirect transmission tests seem to be the only available testing option. All that aforementioned difficulties in applying the UPV method may sometimes make prohibitive its practical use.

The pioneering idea of embedding the piezoelectric transducers directly inside the cementitious material occurred to Gu et al at the University of Houston [116]. They successfully designed and manufactured PZT (lead-zirconate-titanate) piezoelectric ceramic transducers in the form of ‘smart aggregates’ which were pre-placed in a mould before casting the concrete and they could be used both as transmitters and receivers of ultrasonic waves. The smart aggregate is a pre-cast concrete block with a small size, waterproof and wired piezoceramic patch. The size of the embedded smart aggregates is comparable with the aggregates used in the concrete mix and the stable coupling between the transducers and the material matrix can ensure accurate and reliable measurement with a quite high signal to noise ratio as well as high level of measurements repeatability. Thus, the presence of the properly embedded smart aggregates does not seem to cause any further heterogeneities or affect the mechanical behavior of the concrete structure. This technique offers the possibility of overcoming possible limitations of traditional methods which prevent the application of specific boundary conditions during the measurement. It is obvious that this method provides a great flexibility in the choice of the arrangement of the transducers and thus it is an ideal in-situ monitoring technique. It can be equally used for the hydration monitoring as well as for monitoring the structural integrity of the cementitious material during its entire service life. Until now, the laboratory applications of the embedded transducers have been mainly focused on new constructions whereas in many cases the biggest concern is the existing, ageing concrete infrastructure.

Various researchers have worked on the topic of using embedded piezoelectric transducers. Gu et al [116] studied the compressive strength development of concrete structures by observing the development of harmonic response amplitude during the early age period. The acquired experimental results revealed that the amplitude of the harmonic response dropped with increasing concrete strength. Except compressive strength monitoring, piezoceramic transducers embedded in concrete have been successfully used for the characterization of the properties of concrete, such as the modulus of elasticity and Poisson’s ratio. The experimental results obtained by using the newly developed embedded piezoelectric transducers were compared with the values obtained from impact-echo test for same batch of concrete and good agreement was observed [15].

Recently Dumoulin et al [14], following the concept of ‘smart aggregate’ (i.e. SMAG), designed and fabricated their own low-cost (<10€/piece) and small-size embedded piezoelectric transducers in order to monitor the compressional ultrasonic wave velocity evolution during the setting and hardening phases of concrete since casting time. Each transducer used in that study consists of a flat ceramic piezoelectric PZT patch (12 mm x 12 mm x 0.2 mm) (figure 6-a) and its electrodes are conductively glued with the cable (figure 6-b). In order to avoid capacitive coupling interference between the transducers due to the presence of water in the fresh cementitious material, the patch should be properly insulated in a waterproof coating using an epoxy (figure 6-c). Additionally, extra electromagnetic shielding is provided by applying a thin layer of conductive (i.e. silver) paint (figure 6-d). Finally, an additional mechanical protection is provided by embedding the final product in a small mortar cylinder (figure 6-e).

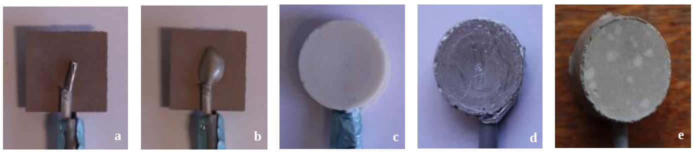

Figure 6. SMAG transducer manufacturing steps.

Before using the transducers, a calibration test was performed in water. The transducers were submerged into the water in order to measure the wave velocity. Knowing that the compressional wave velocity in water is 1498 m/s and measuring accurately the distance between the transducers, the validity of the technique was verified and the time delay of the transducers was calculated. Additionally, the insulation of the transducers was also checked. Figure 7 shows a typical signal of the ultrasonic longitudinal wave acquired by the receiver. The input signal is a short-duration high-voltage (800V / 2.5 μs) pulse and the amplitude of the received signal is in the range of 0.2 V and it can be seen that there is a limited (coupled) interference from the input pulse.

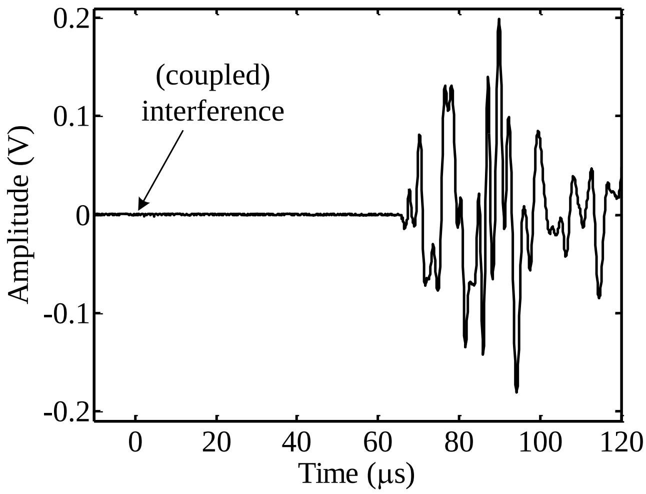

Figure 7. Ultrasonic longitudinal wave with limited (coupled) interference.

Before casting the concrete in a prismatic mould, the SMAGs had been already symmetrically to the centre of the mould fixed at a between distance of 6 cm, which is equivalent to the distance of external transducers used in a dedicated mould of a commercial system called FreshCon system [104, 117] developed at the University of Stuttgart. The same concrete was cast in both moulds. The evolution of the compressional ultrasonic wave propagation velocity was monitored during the first 24 hours after concrete casting. According to figure 8, the first parts of the curves do not seem to agree, but these results occur before the setting. That relative error is obviously decreased after the setting and then the curves are almost superimposed. Those discrepancies before the setting could be due to different air content in the different moulds as well as differences in the frequency content of the excitation pulse which are very important before the material hardens [106]. Carette et al [118] evaluated the relevance of SMAG technique compared to FreshCon system for monitoring the progression of dynamic modulus of elasticity and the results are in very good agreement.

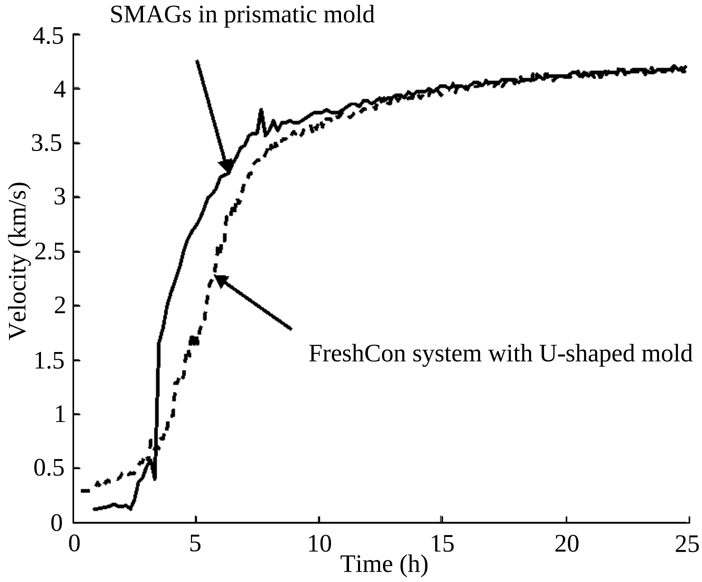

Figure 8. Comparison of the measured compressional ultrasonic wave propagation velocity as a function of time using the commercial FreshCon system and the laboratory made SMAGs [14].

In addition to the early-age strength monitoring of cementitious materials, the embedded piezoelectric transducers have been already successfully used in SHM applications [119-121]. Song et al [119] and Laskar et al [120] used embedded piezoceramic transducers for damage detection of large scale reinforced concrete structures under static loading. The crack or damage inside the concrete acts as a stress relief in the wave propagation path and thus the amplitude of the wave and the transmission energy will decrease. The proposed method had the ability not only to detect the generation of cracks, but also to monitor the growth of them. Due to its great sensitivity, the structural failure was predicted earlier than its visual confirmation. Gu et al [121] verified the effectiveness of the proposed smart aggregate embedded in large scale reinforced concrete columns under dynamic seismic excitation. Another important problem that needs to be solved is the optimal transducer placement in the structure. Sun and Yan [122] studied the concept of a transducer array resolution for damage identification. Recently, Dumoulin et al [123] used SMAGs in order to detect and follow the crack propagation in a reinforced concrete beam subjected to a three-point bending test. The results revealed a high sensitivity of the method which was able to pick-up the crack generation and monitor its propagation until the complete failure of the beam with a simple and efficient damage index (figure 9).

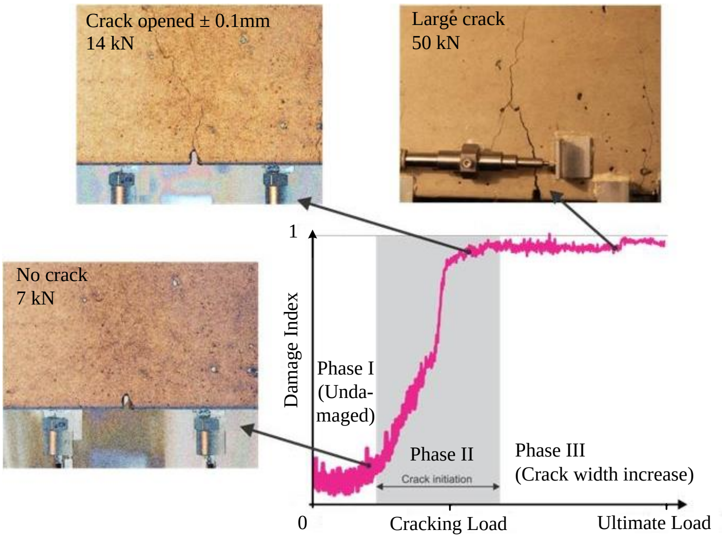

Figure 9. Damage index evolution as a function of the load for the reinforced concrete beam, comparison with the visual observations [123].

In addition, Karaiskos et al [124] implemented an on-line monitoring system to detect and follow the evolution of cracking during three pull-out tests on concrete blocks to which highway safety rails are attached. The change of the signals is well captured by the damage index as shown in figure 10 where its evolution is plotted as a function of the applied load for two pairs (i.e. three transducers which form a one transmitter and two receiver arrangement) of embedded transducers in each of the blocks. The comparison of the results for the three concrete blocks shows that there is a large test-to-test variability which was well captured with the monitoring system. In each case, the system was able to catch the initiation (phase I) of damage as well as the progressive (phase II) and the sudden (phase III) damage events until complete failure.

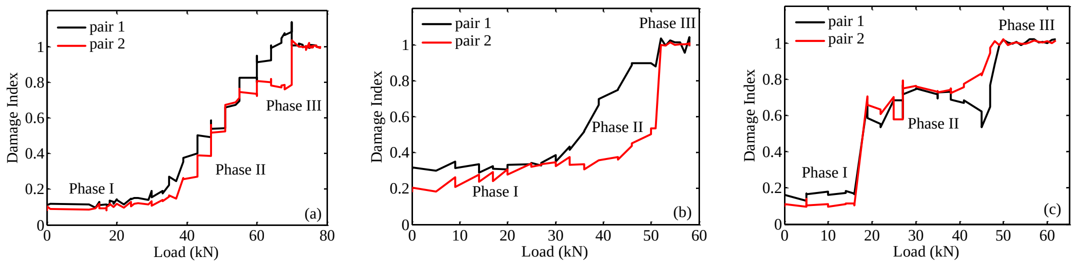

Figure 10. Damage index evolution as a function of the load for both pairs of embedded transducers in the (a) 1st, (b) 2nd and (c) 3rd concrete blocks.

A new area of concrete research is the autonomous self-healing (SH) systems using embedded glass capsules filled with healing agent [125]. These systems promise material recovery and service life extension by filling the generated cracks with appropriate healing agent providing healing and sealing. Recently, Tsangouri et al [126] used for the first time the aforementioned ultrasonic wave propagation technique based on SMAGs in order to evaluate not only the gradual crack formation due to loading but also the healing and fracture recovery of four small-size concrete beams where in three of them SH encapsulated system was embedded. The first beam was the reference one (empty glass capsules were only embedded) and only one pair of SMAGs was embedded. In the second and third beams only one pair of SMAGs was also embedded and in the fourth one, two pairs of SMAGs were embedded for better monitoring of the crack generation, propagation, healing and sealing (figure 11).

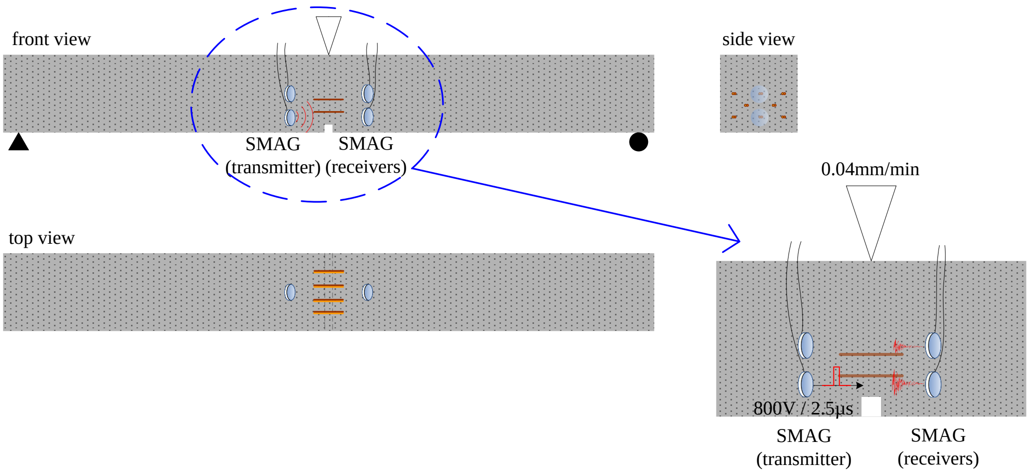

Figure 11. The SMAGs and capsules with healing agent configuration in the fourth beam.

Before loading the reference beam and during its early age period, the compressional ultrasonic wave propagation velocity was monitored during the first 70 hours after concrete casting. By taking into account the calculated time delay of the transducers, computed through a calibration test before embedding them in the concrete, and the distance between them, the evolution of the UPV as a function of time for the monitored early-age period was calculated (figure 12). A few recorded signals at different times are also shown in figure 12. It is obvious that the signal to noise ratio and the maximum amplitude of the recorded signals gradually increase and the transit time T is decreased during the transition from fluid to solid.

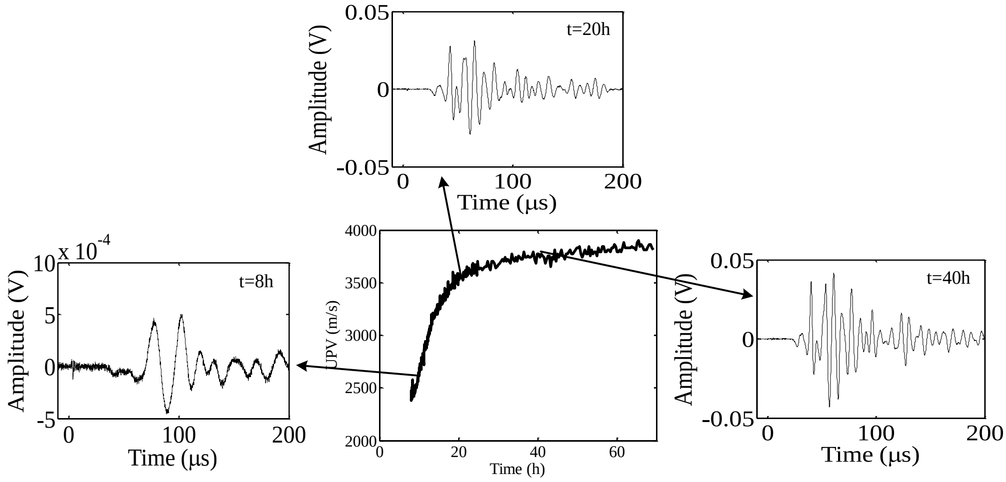

Figure 12. Evolution of the UPV as a function of time for the reference beam.

The maximum amplitude of the recorded signals at very early-age period is however about one hundred times smaller than the one at an age of 60 h and afterwards. Using equation (3) and assuming a dynamic Poisson's ratio equal to 0.3, the dynamic modulus of elasticity of the concrete during the same early-age is computed and its progression is shown in figure 13.

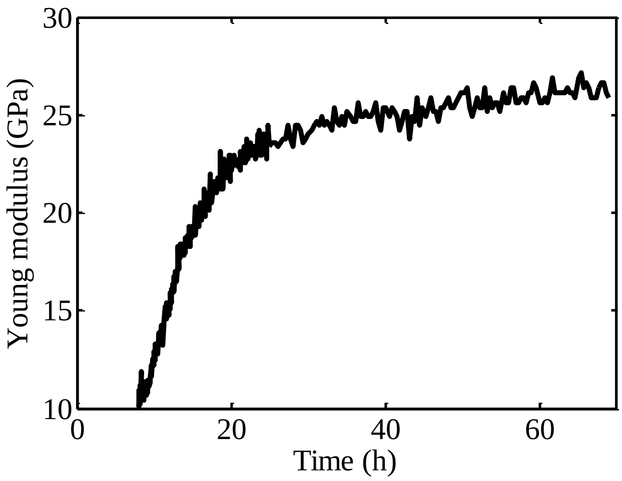

Figure 13. Evolution of the dynamic modulus of elasticity as a function of time for the reference beam.

After concrete hardening, the loading was applied in two stages. In the first stage, the capsules were ruptured and the agent was released activating the healing process. After a 24h curing period, the concrete beams were reloaded under the same conditions (figure 11). The damage index [124] considered both the shift of the arrival time and the amplitude of the received signals. Thus any increase of the calculated damage index is indicative of crack formation and extension. In figure 14, the damage index evolution as a function of the applied loading for the second and fourth beam consists of three phases. The initiation (phase I), progression (phase II) and total failure (phase III) of the beams are clearly detected.

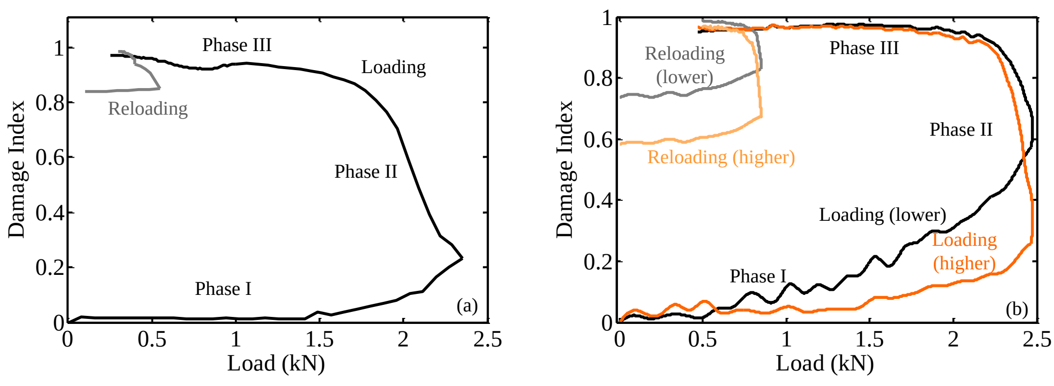

Figure 14. Damage index evolution as a function of the load for (a) the 2nd and (b) 4th concrete beams.

In the second beam, four couples of glass capsules filled with limited healing agent and a pair of SMAGs were embedded. Limited sealing of the cracked area and almost no mechanical recovery was achieved. In the fourth beam, a greater amount of healing agent was used (i.e. eight couples of glass capsules filled with healing agent) and two pairs of SMAGs were embedded (figure 11). Sufficient damage recovery was achieved. During the tests on the fourth beam, one of the lower placed SMAGs was used as the transmitter and the two opposite SMAGs were used as the receivers. It is worth to be noted that the damage index calculated by the signals received by the lower placed SMAG (receiver) grew first and before the respective damage index using the signals received by the higher placed SMAG. This makes great sense because the first SMAG combination monitored an area which is closer to the point of crack initiation than the second SMAG combination. In the reloading test, the initial damage index value of the lower placed SMAG combination is greater than the respective one of the higher placed SMAG combination. This is a good indicator that the present monitoring method could be used to track not only the initiation and evolution of the crack, but also its healing.

4. Conclusions and perspectives

Concrete will continue to be the leading structural material for the next years due to its still low production cost and high structural design flexibility. As an heterogeneous material, the development and application of reliable and affordable non-destructive testing (NDT) methods for structural integrity and strength assessment are highly demanding. Ultrasonic Pulse Velocity (UPV) method is a reliable and simple concrete NDT method providing high potential solutions for nondestructive evaluation of new and existing concrete infrastructure. A change in the pulse velocity of a tested concrete specimen is closely related to a change in elastic modulus. The elastic modulus and the compressive strength are not linearly related, but a series of factors such as the type and amount of aggregates, the water-to-cement ratio, the presence of steel reinforcement as well as the hydration and curing conditions have a strong influence on the relationship between the pulse velocity and compressive strength. Over the years, that method has been widely used for different purposes, such as the monitoring and quality assessment of the hydration process (i.e. setting and hardening period), the strength estimation, as well as the damage assessment in cementitious materials. The conventional UPV method is based on the use of external piezoelectric transducers and some of the drawbacks of the through-transmission arrangement of transducers are the need for access to both sides of the tested concrete structure and the lack of information on the location of a detected flaw. Today, UPV method continues to be a reliable and well promising NDT method based on quick measurements using affordable equipment [127].

The field application of the UPV method in new structures should be cost effective and time efficient without interfering in the construction process of the infrastructure. For that reason, a good alternative to the usual UPV measurement technique is using embedded low-cost and small-size piezoelectric transducers, especially since they can be successfully used for in-situ applications requiring particular boundary conditions. The embedded piezoelectric transducer based approach has a tremendous potential to efficiently serve as an effective tool for performing comprehensive monitoring of concrete structures. Monitoring the hydration process of the in-situ concrete structures, the construction period can be quickly and safely shortened. That inexpensive NDT method effectively meets the health monitoring requirements of concrete structures from the early age until the end of their operational service life. It is worth further exploring this new idea by designing appropriate ways to use this technique not only in new constructions, but also in existing, ageing ones by properly fixing the transducers into a drilled hole in the hardened concrete.

Further studies will be focused on the exploitation of the received signals to give a quantitative evaluation of damage taking into account the complex reflections and scattering due to its constituent elements. One possible route could be the multiple feature extraction from the measured signals in order to possibly train an artificial neural network to predict the size of the damage. Further studies focused on a deeper understanding of the stress wave propagation methods should be developed through analytical and numerical models. The development of state-of-the-art multiphysics finite element numerical models is moving in the right direction. In addition, the fundamental understanding, systematic observation and evaluation of the healing, sealing and recovery of concrete cracked plane which can be efficiently achieved with the continuous monitoring offered by the UPV method using embedded piezoelectric transducers is a new field in concrete research. For the first time, an on-line UPV monitoring system was successfully used for monitoring and evaluating the healing performance in the cracked area of a concrete structure. It is worth to be noted that due to the great sensitivity of the monitoring technique, the crack evolution and the allocation of the released healing agent at different heights of the beam were well detected. The results of those initial applications using embedded piezoelectric transducers are very promising in order to use that technique in more complex test configurations.

In order to develop a reliable on-line NDT method for in-situ applications, it is necessary to filter out any possible environmental effect, such as temperature variations and humidity, from the received signals through advanced post processing techniques. Additionally, the concept of embedded piezoelectric transducers needs further research and some light should be shed in the coupling between the transducers and the concrete because it is mainly still based on the experience. Improvements on the calibration methodology of the transducers should be also carried out. When the transducers are embedded in the material, the constraint from the surrounding material has to be considered. With continuous hydration, the hardness of concrete increases and the boundary conditions of the embedded transducers change. The change of the transducer properties may be reflected in the ultrasonic wave propagation characteristics. In order to measure the properties changes of the transducers, the impedance spectra should be analyzed and explained. According to figures 5 and 12, the extraction of the wave velocity with a good accuracy at very early age is difficult and some possible improvements could be achieved by using optimized and more powerful excitation pulsers and transducers. Monitoring the shear waves using embedded piezoelectric transducers is a further study that has to be carried out. Last but not least, the in-situ application of the UPV method should be cost effective and time efficient without interfering in the construction process of the infrastructure.

In any case, the ultrasonic evaluation of concrete is a wide and very promising field for both fundamental and applied research. It is strongly believed that a more efficient maintenance and operation of concrete facilities can be achieved, thus contributing towards a safer and more secure society.

References

[1] Perkins P H 1997 *Repair, Protection and Waterproofing of Concrete Structures* (London UK: Spon Press) p 256

[2] Mehta P K 1991 Durability of concrete-Fifty years of progress? *Durability of concrete: 2nd Int. Conf. Concrete Durability ACI SP-126* (Montreal, Canada) pp 1-31

[3] ACI 224.1-R07 2007 *Causes, evaluation and repair of cracks in concrete structures* (Farmington Hills, Michigan, USA: American Concrete Institute)

[4] Kelly J W 1981 Cracks in concrete: part 1, part 2, *Concrete Constr.* **26** 725-34

[5] Price W H 1982 Control of cracking during construction, *Concrete Intern.* **4** 40-43

[6] Transportation Research Board of the National Academies 2006 Control of cracking in concrete – state of the art (Transportation Research Circular) **E-C107** p 56

[7] Nilsson A H and Winter G 1985 *Design of Concrete Structures* (McGraw Hill)

[8] Nawy E G 2001 *Fundamentals of High Performance Concrete* (Wiley) p 464

[9] Jones R 1962 *Non-Destructive Testing of Concrete* (London UK: Cambridge University Press) p 103

[10] ACI 437R-03 2003 *Strength evaluation of existing concrete buildings* (Farmington Hills, Michigan, USA: American Concrete Institute)

[11] ACI 228.1R-03 2003 *In-place methods to estimate concrete strength* (Farmington Hills, Michigan, USA: American Concrete Institute)

[12] ACI 228.2R-13 2013 *Report on nondestructive test methods for evaluation of concrete in structures* (Farmington Hills, Michigan, USA: American Concrete Institute)

[13] Popovics S 1998 *Strength and Related Properties of Concrete: A Quantitative Approach* (Wiley) p 535

[14] Dumoulin C, Karaiskos G, Carette J, Staquet S and Deraemaeker A 2012 Monitoring of the ultrasonic P-wave velocity in early-age concrete with embedded piezoelectric transducers *Smart Mater. Struct.* **21** 047001

[15] Li Z, Qin L and Huang S 2009 Embedded piezo-transducer in concrete for property diagnosis *J. Mater. Civil Eng.* **21** 643-7

[16] Rayleigh J W S 1894 *The Theory of Sound* (London: MacMillan)

[17] Curie J and Curie P 1880 Development via compression of electric polarization in hemihedral crystals with inclined faces (Développement par compression de l'électricité polaire dans les cristaux hémièdres à faces inclinées) *Bul. de la Société minérologique de France* **3** 90-93

[18] Lippmann G 1881 Principe de la conservation de l'électricité *Annales de chimie et de physique* **24**

[19] Long B G, Kurtz H J and Sandenaw T A 1945 An Instrument and a technique for field determination of elasticity, and flexural strength of concrete (pavements) *J. Am. Concrete I.* **41** 217-31

[20] Jones R 1949 The non-destructive testing of concrete *Mag. Concrete Res.* **2** 67-78

[21] Leslie J R and Cheesman W J 1949 An ultrasonic method of studying deterioration and cracking in concrete structures *J. Am. Concrete I.* **21** 17-36

[22] Parker W E 1953 Pulse velocity testing of concrete *Proc. ASTM* **53** 1033-42

[23] Whitehurst E A 1951 Soniscope tests concrete structures *J. Am. Concrete I.* **47** 433-48

[24] Whitehurst E A 1966 *Evaluation of Concrete Properties from Sonic Tests* American Concrete Institute Monograph No. 2 (Farmington Hills, Michigan, USA: American Concrete Institute) p 94

[25] Jones R 1949 Measurement of the thickness of concrete pavements by dynamic methods: A survey of the difficulties *Mag. Concrete Res.* **1** 31-34

[26] Jones R 1953 Testing of concrete by ultrasonic-pulse technique, *Proc. Highway Research Board* National Research Council USA **32** 259-75

[27] ASTM C 597 – 67 1967 Standard test method for pulse velocity through concrete (American Society for Testing and Materials (ASTM))

[28] Leslie J R 1955 Proposed tentative method of test for the measurement of the pulse velocity of propagation of elastic waves in concrete *ASTM Bul.* **204** 19-22

[29] Jones R and Facaoaru I 1969 Recommendations for testing concrete by the ultrasonic pulse method *Mater. Struct.* **2** 275-84

[30] Facaoaru I 1969 Chairman's report, meeting of RILEM TC on Non-Destructive Testing of concrete, Varna, September 1968, *Mater. Struct.* **2** 253-67

[31] Elvery R H 1973 Estimating strength of concrete in structures *Concrete* **11** 49-51

[32] Carino N J, Woodward K A, Leyendecker E V and Fattal S G 1983 Review of the Skyline Plaza collapse *Concr. Int.: Design & Construction* **5** 35-42

[33] Lew H S 1980 West Virginia cooling tower collapse caused by inadequate concrete strength *Civil Eng.* **50** 62-67

[34] Bungey J H, Millard S G and Grantham M G 2006 *Testing of Concrete in Structures* (Taylor & Francis) p 352

[35] Farrar C R and Worden K 2012 *Structural Health Monitoring: A Machine Learning Perspective* (Wiley) p 654

[36] Naik T R, Malhorta V M and Popovics J S 2004 *The Ultrasonic Pulse Velocity Method* in *Handbook on Nondestructive Testing of Concrete*, ed V M Malhorta and N J Carino (CRC Press) p 384

[37] Graff K F 1975 *Wave Motion in Elastic Solids* (Dover Publications) p 649

[38] Krautkrämer J and Krautkrämer H 1969 *Ultrasonic Testing of Materials* (G. Allen & Unwin) p 521

[39] Teodorou G V 1988 The use of simultaneous nondestructive tests to predict the compressive strength of concrete *Nondestructive Testing* SP-112 (Farmington Hills, Michigan, USA: American Concrete Institute)

[40] Carino N J 1993 Nondestructive testing of concrete: history and challenges, ACI SP-144: Concrete Technology: Past, Present, and Future (Farmington Hills, Michigan, USA: American Concrete Institute)

[41] RILEM Technical Committee 207-INR 2012 Non-Destructive Assessment of Concrete Structures: Reliability and Limits of Single and Combined Techniques, ed D Breysse (Springer) p 374

[42] Shiotani T and Aggelis D G 2009 Wave propagation in cementitious material containing artificial distributed damage *Mater. Struct.* **42** 377-84

[43] Doyle P A and Scala C M 1978 Review of crack depth measurement by ultrasonics: a review *Ultrasonics* **16** 164-70

[44] Aggelis D G, Hadjiyiangou S, Chai H K, Momoki S and Shiotani T 2011 Longitudinal waves for evaluation of large concrete blocks after repair *NDT&E Int.* **44** 61-66

[45] Tsangouri E, Karaiskos G, Aggelis D G, Deraemaeker A and Van Hemelrijck D 2015 Crack sealing and damage recovery monitoring of a concrete healing system using embedded piezoelectric transducers *Structural Health Monitoring* (accepted for publication)

[46] RILEM NDT 1 1972 Testing of concrete by the ultrasonic pulse method (RILEM)

[47] BS 1881: Part 203 1997 Testing Concrete - Recommendations for measurement of velocity of ultrasonic pulses in concrete (London, UK: British Standards Institute) p 27

[48] EN 12504-4 2003 Testing concrete – Part 4: Determination of ultrasonic pulse velocity (European Committee for Standardization)

[49] Popovics J S, Song W, Achenbach J D, Lee J H and Andre R F 1998 One-sided stress wave velocity measurement in concrete *J. Eng. Mech.-ASCE* **124** 1346-53

[50] Chung H W and Law K S 1985 Assessing fire damage of concrete by the ultrasonic pulse technique *Cement Concrete Aggr.* **7** 84-8

[51] Benedetti A 1998 On the ultrasonic pulse propagation into fire damaged concrete *ACI Structural Journal* **95** 259-71

[52] Cioni P, Croce P and Salvatore W 2001 Assessing fire damage to r.c. elements *Fire Safety J.* **36** 181-99

[53] Teodoru G V M and Herf J 1996 Engineering society Cologne presents itself (NDT methods) *Proc.14th World Conf. on NDT* ed C G Krishnadas et al (New Delhi, India: Oxford & IBH Publishing Co.) pp 939-43

[54] Lee J H, Park W S, Popovics J S and Achenbach J D 1999 Application of one-sided stress wave velocity measurement technique to evaluate freeze-thaw damage in concrete *Rev. Prog. Quant. Nondestr. Eval.* **18A** 1935-42

[55] Shiotani T, Momoki S, Chai H, and Aggelis D G 2009 Elastic wave validation of large concrete structures repaired by means of cement grouting *Constr. Build. Mater.* **23** 2647-52

[56] Chai H, Aggelis D G, Momoki S, Kobayashi Y and Shiotani T 2010 Single-side access tomography for evaluating interior defect of concrete *Constr. Build. Mater.* **24** 2411–8

[57] Ohtsu M and Alver N 2009 Development of non-contact SIBIE procedure for identifying ungrouted tendon duct *NDT&E Int.* **42** 120–7

[58] Aggelis D G, Shiotani T and Polyzos D 2009 Characterization of surface crack depth and repair evaluation using Rayleigh waves *Cement Concrete Comp.* **31** 77-83

[59] Victorov I A 1967 *Rayleigh and Lamb Waves: Physical Theory and Applications* (Plenum Press) p 154

[60] Kaplan M F 1960 The relation between ultrasonic pulse velocity and the compressive strength of concretes having the same workability but different mix proportions *Mag. Concrete Res.* **12** 3-8

[61] Popovics S 2001 Analysis of the concrete strength versus ultrasonic pulse velocity relationship *Mater. Eval.* **59** 123-30

[62] Lin Y, Lai C P, and Yen T 2003 Prediction of ultrasonic pulse velocity in concrete *ACI Mater. J.* **100** 21-28

[63] Ye G, Van Breugel K, and Fraaij A L A 2001 Experimental study on ultrasonic pulse velocity evaluation of the microstructure of cementitious material at early age *Heron* **46** 161-7

[64] Abo-Qudais S A 2005 Effect of concrete mixing parameters on propagation of ultrasonic waves *Constr. Build. Mater.* **19** 257-63

[65] Kaplan M F 1959 The effects of age and water to cement ratio upon the relation between ultrasonic pulse velocity and compressive strength of concrete *Mag. Concrete Res.* **11** 85-92

[66] Trtnik G, Kavcic F, and Turk G 2009 Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks *Ultrasonics* **49** 53-60

[67] Sturrup V R, Vecchio F J and Caratin H 1984 Pulse velocity as a measure of concrete compressive strength *J. Am. Concrete I.* **82** 201-28

[68] Evangelista A C, Shehata A I and Shehata L 2003 Parameters that influence the results of non-destructive test methods for concrete strength *Int. Symp. In Non-Destructive Testing in Civil Engineering (NDT-CE)* (Berlin)

[69] Madandoust R, Ghavidel R, and Nariman-Zadeh N 2010 Evolutionary design of generalized GMDH-type neural network for prediction of concrete compressive strength using UPV *Comp. Mater. Sci.* **49** 556-67

[70] Ohdaira E, and Masuzawa N 2000 Water content and its effect on ultrasound propagation in concrete – the possibility of NDE *Ultrasonics* **38** 546-52

[71] Yamaguchi T and Yamaguchi T 2000 Measurement of thickness and crack depth in concrete by ultrasonic methods *Symp. and Seiken Symp. 26 (NDT-CE)* (Oxford, UK: Elsevier) pp 331-40

[72] Chung H W 1978 Effects of embedded steel bars upon ultrasonic testing of concrete *Mag. Concr. Res.* **30** 19-25

[73] Teodoru G V 1986 Mechanical strength property of concrete at early ages as reflected by schmidt rebound number, ultrasonic pulse velocity, and ultrasonic attenuation, properties of concrete at early ages SP-95, ed J F Young (Farmington Hills, Michigan, USA: American Concrete Institute) pp 139-53

[74] Kheder G F Al Gabban A M and Abid S M 2003 Mathematical model for the prediction of cement compressive strength at the ages of 7 and 28 days within 24 hours *Mater. Struct.* **36** 693-701

[75] Krishna Rao M V, Ratish Kumar P and Khan A M 2010 A study on the influence of curing on the strength of a standard grade concrete mix *Facta Universitatis (Series Architecture and Civil Engineering)* **8** 23-34

[76] Yazicioglu S, Caliskan S and Turk K 2006 Effect of curing conditions on the engineering properties of self-compacting concrete *Indian J. Eng. Mater. S.* **13** 25-29

[77] Tanyidizi H and Coskun A 2008 Determination of the principal parameter of ultrasonic pulse velocity and compressive strength of lightweight concrete by using variance method *Russ. J. Nondestruct.* **44** 639-46

[78] Carino N J 2004 *Stress Wave Propagation Methods* in *Handbook on Nondestructive Testing of Concrete*, ed V M Malhorta and N J Carino (CRC Press) p 384

[79] Sansalone M and Carino N J 1986 Impact echo, a method for flaw detection in concrete using transient stress waves Report No. NBSIR 86-3452 (National Bureau of Standards)

[80] Sansalone M and Streett W B 1997 *Impact-Echo: Nondestructive Testing of Concrete and Masonry* (Bullprier Press) p 339

[81] BS EN 13554 2011 Non-destructive testing. Acoustic emission testing. General orinciples (British Standards Institution)

[82] Grosse C U and Ohtsu U 2008 *Acoustic Emission Testing* (Springer) p 406

[83] Clemena G G 2004 *Short-Pulse Radar Methods* in *Handbook on Nondestructive Testing of Concrete*, ed V M Malhorta and N J Carino (CRC Press) p 384

[84] Daniels D J 2004 *Ground penetrating radar* (Institution of Electrical Engineers) p 726

[85] Mitchell T M 2004 *Radioactive/Nuclear Methods* in *Handbook on Nondestructive Testing of Concrete*, ed V M Malhorta and N J Carino (CRC Press) p 384

[86] ASTM D 4788 – 03 2013 *Standard test method for detecting delaminations in bridge decks using infrared thermography* (American Society for Testing and Materials (ASTM))

[87] Maldague X P 2001 *Theory and Practice of Infrared Technology for Nondestructive Testing* (Wiley) p 704

[88] Weil G J 2004 *Infrared Thermographic Techniques* in *Handbook on Nondestructive Testing of Concrete*, ed V M Malhorta and N J Carino (CRC Press) p 384

[89] ASTM C805 / C805M – 13a 2013 *Standard test method for rebound number of hardened concrete* (American Society for Testing and Materials (ASTM))

[90] Kim J K, Kim C Y, Yi S T and Lee Y 2009 Effect of carbonation on the rebound number and compressive strength of concrete *Cement Concrete Comp* **31** 139-144

[91] Skramtaev B G and Leshchinsky M Y 1966 Complex methods of non-destructive tests of concrete in constructions and structural works *RILEM Bull.* **30** 99-105

[92] Wiebenga J G 1968 A comparison between various combined non-destructive testing methods to derive the compressive strength of concrete Rep. kB1-68-61/1418 (Delft, the Netherlands: Inst. TNO Veor Bouwmaterialen en Bouwconstructies)

[93] Facaoaru I 1970 Non-destructive testing of concrete in Romania *Symp. On NDT of concrete and timber* (London: ICE) pp 39-49

[94] RILEM Technical Committee 43 CND 1983 *In situ strength estimation by combined non-destructive methods* (RILEM)

[95] Teodoru G V 1988 The use of simultaneous nondestructive tests to predict the compressive strength of concrete *Nondestructive Testing* SP-112, ed H S Lew (Farmington Hills, Michigan, USA: American Concrete Institute) pp 137-52

[96] Samarin A 2004 *Combined Methods* in *Handbook on Nondestructive Testing of Concrete*, ed V M Malhorta and N J Carino (CRC Press) p 384

[97] Qasrawi H Y 2000 Concrete strength by combined nondestructive methods simply and reliably predicted *Cem. Concr. Res.* **30** 739-46

[98] Grosse C U and Reinhardt H W 2000 Ultrasound technique for quality control of cementitious materials *15th World Conf. on NDT* (Rome)

[99] EN 196-3 2008 Methods of testing cement – Part 3: Determination of setting time and soundness (European Committee for Standardization)

[100] ASTM C 403 – 08 2008 Standard test method for time of setting of concrete mixtures by penetration resistance (American Society for Testing and Materials (ASTM))

[101] Trtnik G, Turk G, Kavèiè F and Bosiljkov V B 2008 Possibilities of using the ultrasonic wave transmission method to estimate initial setting time of cement paste *Cement Concrete Res.* **38** 1336-42

[102] Keating J, Hannant D J and Hibbert A P 1989 Correlation between cube strength, ultrasonic pulse velocity and volume change for oil well cement slurries *Cement Concrete Res.* **19** 715-26

[103] Reinhardt H W, Grosse C U and Herb A T 2000 Ultrasonic monitoring of setting and hardening of cement mortar – a new device *Mater. Struct.* **33** 580-3

[104] Reinhardt H W and Grosse C U 2004 Continuous monitoring of setting and hardening of mortar and concrete *Constr. Build. Mater.* **18** 145–54

[105] Zhang J, Qin L and Li Z 2009 Hydration monitoring of cement-based materials with resistivity and ultrasonic methods *Mater. Struct.* **42** 15-25

[106] Aggelis D G, Polyzos D and Philippidis T P 2005 Wave dispersion and attenuation in fresh mortar: theoretical predictions vs. experimental results *J. Mech. Phys. Solids* **53** 857–83

[107] Aggelis D G and Philippidis T P 2004 Ultrasonic wave dispersion and attenuation in fresh mortar *NDT&E Int.* **37** 617–31

[108] Philippidis T P and Aggelis D G 2005 Experimental study of wave dispersion and attenuation in concrete *Ultrasonics* **43** 584–95

[109] Aggelis D G and Shiotani T 2007 Experimental study of surface wave propagation in strongly heterogeneous media *J. Acoust. Soc. Am.* **122** EL151-157

[110] Sayers C M and Dahlin A 1993 Propagation of ultrasound through hydrating cement pastes at early times *Adv. Cem. Based Mater.* **1** 12-21

[111] Chen W, Shui Z and Li W 2010 Early age hydration of cement paste monitored with ultrasonic velocity and numerical simulation *J. Wuhan Univ. Technol.* **25** 704-7

[112] Chotard T, Gimet-Breart N, Smith A, Fargeot D, Bonnet J P and Gault C 2001 Application of ultrasonic testing to describe the hydration of calcium aluminate cement at the early age *Cement Concrete Res.* **30** 405-12

[113] Qin L and Li Z 2008 Monitoring of cement hydration using embedded piezoelectric transducers *Smart Mater. Struct.* **17** 055005

[114] Mohammed B S, Azmi N J and Abdullahi M 2011 Evaluation of rubbercrete based on ultrasonic pulse velocity and rebound hammer tests *Constr. Build. Mater.* **25** 1388-97

[115] De Belie N, Grosse C U and Reinhardt H W 2005 Ultrasound monitoring of setting and hardening of shotcrete including alkali-rich or alkali-free accelerators *2nd Int. Conf. on Concrete Repair, Rehabilitation and Retrofiting (ICCRRR-2) (Cape Town, South Africa)*

[116] Gu, H, Song G, Dhonde H, Mo YL and Yan S 2006 Concrete early-age strength monitoring using embedded piezoelectric transducers *Smart Mater. Struct.* **15** 1837-45

[117] Robeyst N, Gruyaert E, Grosse C U and De Belie N 2008 Monitoring the setting of concrete containing blast-furnace slag by measuring the ultrasonic p-wave velocity *Cement Concrete Res.* **38** 1169-76

[118] Carette J, Dumoulin C, Karaiskos G, Staquet S and Deraemaeker A 2012 Monitoring of the E-modulus in early age concrete since setting time with embedded piezoelectric transducers *Structural Faults and Repair: 14th Int. Conf. and Exhibition (Edinburg, Scotland, UK)*

[119] Song G, Gu H, Mo Y L, Hsu T T C and Dhonde H 2007 Concrete structural health monitoring using embedded piezoceramic transducers. *Smart Mater. Struct.* **16** 959-68

[120] Laskar A, Gu H, Mo Y L and Song G 2009 Progressive collapse of a two-story reinforced concrete frame with embedded smart aggregates *Smart Mater. Struct.* **18** 075001

[121] Gu H, Moslehy Y, Sanders D and Song G 2010 Multi-functional smart aggregate-based structural health monitoring of circular reinforced concrete columns subjected to seismic excitations *Smart Mater. Struct.* **19** 065026

[122] Sun W and Yan S 2008 Health monitoring strategy for smart piezoelectric concrete structures *Proc. SPIE 6932, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems* doi:10.1117/12.775205

[123] Dumoulin C, Karaiskos G, Sener J-Y and Deraemaeker A 2014 On-line monitoring of cracking in concrete structure using embedded piezoelectric transducers *Smart Mater. Struct.* **23** 115016

[124] Karaiskos G, Flawinne S, Sener J-Y and Deraemaeker A 2013 Design and validation of embedded piezoelectric transducers for damage detection applications in concrete structures *10th Int. Conf. on Damage Assessment of Structures (DAMAS 2013) (Trinity College, Dublin, Ireland)*

[125] Dry C M 1994 Matrix cracking repair and filling using active and passive modes for smart timed release of chemicals from fibers into cement matrices, *Smart Mater. Struct.* **3** 118–23

[126] Tsangouri E, Karaiskos G, Aggelis D G, Van Hemelrijk D and Deraemaeker A 2014 Healing performance on concrete under mode I fracture by ultrasonic testing using embedded transducers, acoustic emission and digital image correlation method *9th Int. Conf. on Structural Dynamics (EURODYN 2014) (Porto, Portugal)*

[127] Panzera T H, Christoforo A L, Cota F P, Borges P H R and Bowen C R 2011 *Ultrasonic Pulse Velocity of Cementitious Materials* in *Advances in Composite Materials – Analysis of Natural and Man-Made Materials,* ed P Tesinova (INTECH) p 584