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Evaluation of Concrete by Non-destructive Ultrasonic Pulse Velocity Method

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Abstract Concrete is a material whose properties depend on its initial formulation, its conditions of use, and its change over time depending on its environment and the different types of degradation that it is likely to undergo. Knowledge and monitoring of its various mechanical properties are therefore essential for the maintenance of civil engineering works. All of the concrete assessment methods, whether destructive or non-destructive, can then provide a valuable diagnosis to the operators of the structure. Depending on their precision, they can be used to easily detect an alteration in the characteristics of the materials, locate a damaged area, the extent of the damage, or even precisely quantify the evolution of this damage over time and predict future changes. This paper presents the Ultrasonic Pulse Velocity technique (UPV) which is used by many companies to assess the compressive strength of concrete in situ and which allows measuring the speed and attenuation of elastic waves. The influence of the reinforcements on the ultrasonic pulse velocity has been studied and this is in the case of reinforcement perpendicular and parallel to the direction of propagation. The influence of several factors affecting the UPV, whether related to the properties of concrete or otherwise, was mentioned. Indeed, the porosity, the water/Cement ratio, the micro-cracks, the state of saturation and the temperature of concrete are parameters which strongly influence the values of UPV.

Keywords Concrete, Ultrasonic Pulse Velocity, Diagnosis, Non-destructive, Compressive Strength

1. Introduction

Most of the properties of concrete are generally evaluated by tests on samples having been made with the same mix as the works (standard test pieces 16/32 for example) or having been taken directly from the works to be examined [1]. These tests are destructive. The resistance measurements Rc and Rt are for example carried out with presses (compression, traction by splitting, by bending, etc.). Porosity can be determined by the volume of mercury or water that can be injected into concrete [2], or by gamma-densimetry [3].

The use of non-destructive methods applicable in situ is essential in cases where it is impossible to take a sample from the structure, or if one wishes to follow the evolution of a characteristic over time. Non-destructive tests are widely applied to study mechanical properties and integrity of concrete structures [4-6].

The main concrete auscultation techniques commonly used in civil engineering are presented in the works of Malhotra and Carino [7], Bungey and Millard [1], Breysse and Abraham [8].

Methods using wave propagation and the interaction of these waves with concrete are among the methods with the greatest potential for the non-destructive evaluation of concrete. Indeed, the properties of wave propagation are directly related to the properties of the material in which they propagate. These waves can be electromagnetic or mechanical and are sensitive to different properties of concrete. They can be used to obtain information at different scales (millimeter, centimeter, or around ten centimeters) depending on the wave length used [8].

A series of methods makes it possible to assess in situ the mechanical resistance at the surface of concrete. Their use is quite widespread and is standardized (European standard EN 13791). Sclerometers are used to measure the hardness of the concrete surface. The rebound height of a mass projected with a certain speed on the concrete surface allows going up to the concrete surface resistance. This device only gives local information on the properties of concrete.

Other methods such as penetration resistance tests (Windsor probe) or pull-out tests of a sealed metal rod in concrete (pull-out) also provide local information on the compressive strength of concrete surface. These methods are partially destructive because they leave impacts and holes in the facing (which can be plugged up easily).

These methods are commonly used on works and can give very useful information to project managers. However, the accuracy remains poor and the information is only local.

The methods using the propagation of electromagnetic waves are the capacitive, resistive, or GPR (Ground Penetration Radar) methods. Low frequency electromagnetic waves can be used to detect metallic elements, and to locate steel reinforcements and estimate their diameter or depth. The metal sheaths of the prestressed cables can also be located, or the presence of large voids in the concrete [9]. These waves are sensitive to the dielectric constants of the medium, and can be used at higher frequencies to go back, after calibration, to the water content [10].

The methods using mechanical waves are based on the propagation of ultrasound in concrete. These waves are sensitive to mechanical properties such as elastic modulus and Poisson's ratio, or even the porosity rate. The most commonly used methods to date are echo impact, sonic auscultation (ultrasonic pulse velocity) and acoustic emission. We can also cite the methods based on seismic tomography or surface waves but which are less used. Acoustic waves can be used to detect cracks, voids, or measure thicknesses. The mechanical properties of concrete can also be assessed after calibration.

These two families of methods provide complementary but nevertheless correlated information [3]. The rest of this work deals only with the propagation of mechanical waves in concrete.

2. The Ultrasonic Pulse Velocity Test

The Ultrasonic Pulse Velocity (UPV) test is based on the principle of the speed of the pulse of a compression wave transmitted through a medium and depends on the elastic properties of this medium.

The measurement of the wave speed in concrete is conventionally used both in the laboratory and on site [7]. This method is also standardized by French [11] and American [12] standards, and there are complete commercial devices allowing this type of measurement to be carried out.

The general principle of UPV test is to measure the speed of the mechanical wave propagating in concrete in transmission, in reflection, or on the surface. A pair of transducers is used for this, one serving as a source and the other as the receiver. This method mainly allows detecting the non-uniformity of the properties of the structure, large cracks or voids resulting for example from “stone nests”. It can also be used to determine the elasticity modulus or the Poisson's ratio of structures [13-15]. However, the UPV measured also depends on many other parameters of the concrete such as heterogeneities, water content, curing conditions, temperature, the presence of micro-cracks, etc.; the values obtained can be very different from those obtained by quasistatic compression tests in the laboratory [16].

The principle of sonic auscultation consists in measuring the propagation time of a wave train between two points. Part of the monitor, the transducer, produces ultrasound. Due to the piezoelectric properties of the materials, the emitted electric energy is converted into ultrasonic mechanical energy. The device measures the time takes for the wave to reach the receiver, which converts it into an electrical signal (Figure 1).

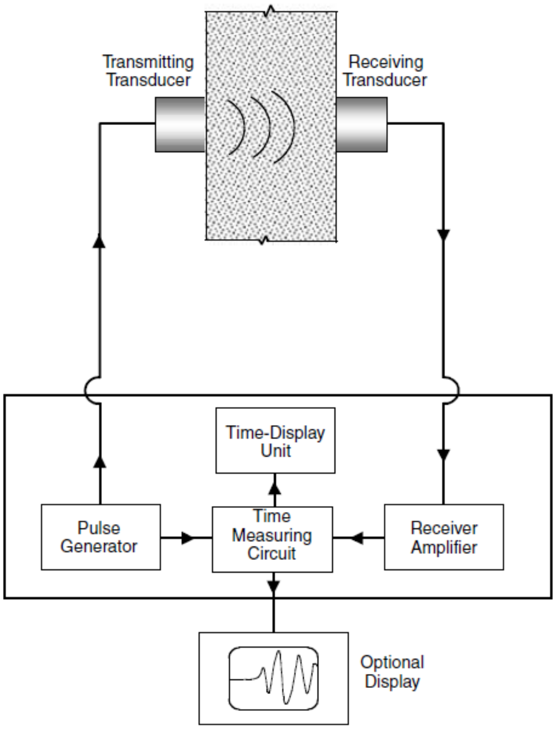

Figure 1. Schematic diagram of UPV test circuit

Knowing the distance L from the transmitter to the receiver, it is possible to know the ultrasonic pulse velocity UPV of the wave by applying the following formula (Eq. 1):

$$\mathrm{UPV} = \frac{L}{T} \qquad (1)$$

Where, L: Distance between two probes (m); T: Time required to travel the distance between two transducers (s).

The relationship between the dynamic modulus of elasticity and the UPV travelling in an isotropic elastic medium of infinite dimensions is given by the following formula (Eq. 2):

$$\mathrm{UPV} = \sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}} \qquad (2)$$

Where: UPV: Ultrasonic pulse velocity (m/s); E: Dynamic elastic modulus (MPa); υ: Dynamic Poisson's ratio; ρ: Density (kg/m^3)

The UPV was determined using Ultrasonic pulse velocity tester "high performance" with microprocessor for combined ultrasonic and rebound hammer data acquisition and processing (Figure 2). It is capable to measure the velocity of the ultrasonic impulse across the material or to measure the distance between probes (if the sonic velocity across the tested element is known). It's also possible to find data about the dynamic elastic modulus and concrete strength. The device used consists of the following accessories:

- Touch-screen colour erminal with LCD 640x480 pixel visual display (A1) complete with internal 64 MB flash memory and a membrane keyboard next to the screen (A2)
- 220 V/24V external power supplier and battery charger
- Two 55kHz piezometric sound probes (A3) with connecting cables
- Calibration cylinder (A4)
- Vaseline pack for probe coupling
- Charger 230V / 24Ve
- Strong shockproof machine and accessories carrying case

The device can also be used to elaborate both ultrasonic tests results and both rebound indexes of sclerometrical tests. It's possible to estimate concrete compressive strength, dynamical elastic modulus and Poisson coefficient. It's also possible to evaluate the presence of voids, internal cracks, etc. into the tested element. Ultrasonic and sclerometric test results combination allows to surpass the limitations of both the methods (if used separately), assuring more accurate and reliable estimations.

There are three methods to conduct the ultrasonic test:

- Direct or transparent measurements (Figure 3(a)) of the longitudinal sound waves through an element. The transmitter (T) and the receiver (R) are placed on the two opposite sides of the element to be examined. It is the most used method because there is a maximum of impulse energy transmitted and then received.
- Semi-direct measurement (Figure 3(b)): the transmitter (T) and the receiver (R) on two perpendicular faces. This method is used when the whole structure is not accessible. The distance between the two transducers should not be too great so that the wave does not attenuate too much and detection of the pulse signal becomes difficult.

Indirect or surface measurements (Figure 3(c)): this method is mainly performed when only one of the faces of the element is accessible or when it is necessary to determine the depth of a crack or the presence of multiple layers in the same element. To carry out this measurement, the transmitter (T) and the receiver (R) must be placed on the same flat face of the element to be examined. The transmitter remains on the same point, while the receiver moves by taking a measurement each time.

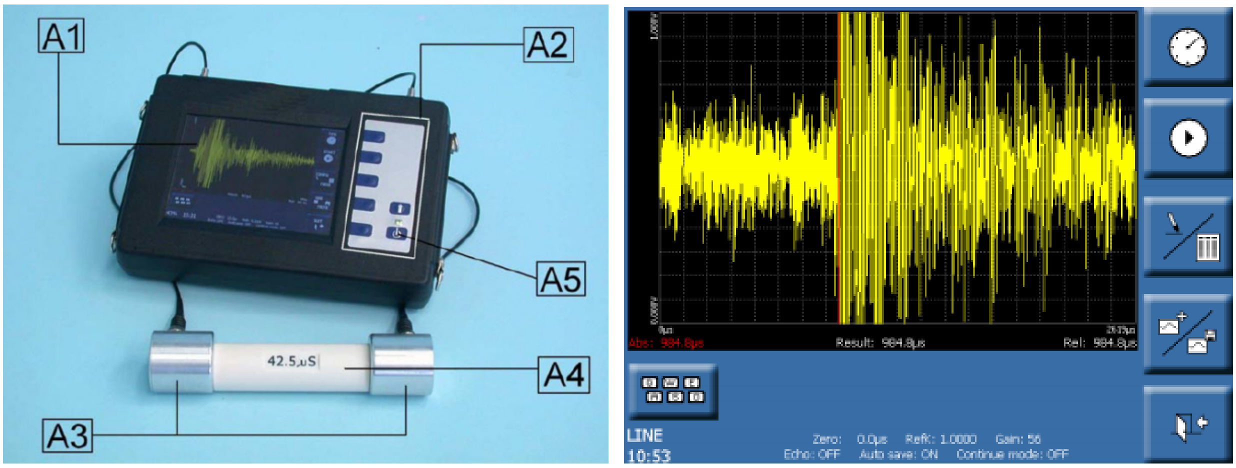

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Figure 2. Ultrasonic Pulse Velocity Tester with microprocessor

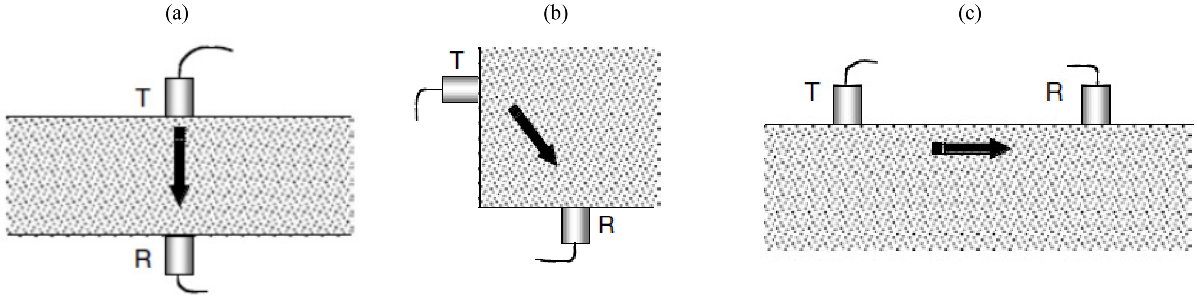

Figure 3. Pulse velocity measurement configurations. (a) Direct method. (b) Semidirect method. (c) Indirect surface method.

The UPV test may directly detect cracking and honeycombing in concrete, without need for detailed correlation of V with any other property of concrete. Since presence of cracking or honeycombing along the pulse path decreases the velocity due to increase in attenuation, the cracking and honeycombing may be detected by observing at a location where measured value of V is found to be less than that found at a sound location.

An estimate of crack depths may be obtained by the use of indirect surface readings (Figure 4). The depth of crack is given by the following formula (Eq. 3):

$$h = X.\left[\sqrt{\left(\frac{T_C}{T_S}\right)^2 \text{-}1}\right] \qquad (3)$$

Where: h: depth of crack; 2X: path length without crack; T_C: transit time observed when the transducers are placed each side of the cracked concrete; T_S: transit time observed when the transducers are placed at sound concrete.

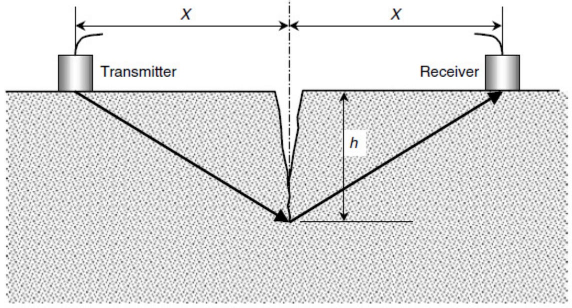

Figure 4. Measurement of surface crack depth

3. Influence of Reinforcements on the Ultrasonic Pulse Velocity

The UPV measured on reinforced concrete, close to the reinforcements, is often higher than that measured in mass concrete of the same composition. In fact, the speed of propagation in steel is 1.2 to 1.9 times greater than that measured in unreinforced concrete.

In some cases, the first impulse that arrives at the transducer has spread partly in the steel and partly in the concrete. The apparent increase in the UPV depends on the proximity of the reinforcements to the location of the measurement points, the section and number of the reinforcements, their positioning relative to the path and the speed of this pulse in coating concrete.

3.1. Reinforcements Perpendicular to the Direction of Propagation

Figure 5 shows the arrangement of the reinforcements perpendicular to the direction of propagation. The maximum influence due to the presence of the reinforcements can be calculated by supposing that during its course the pulse crosses the total section of each of the reinforcements. If "n" concrete reinforcements of diameter Qi (i varying from 1 to n) are directly on the path of the impulse, their axes making right angles to the path of the propagation, we can write the following formula (Eq. 4):

$$\frac{V_C}{V} = \frac{1-\frac{L_S}{L}}{1-\frac{L_S.V}{L.V_S}} \qquad (4)$$

Where: V: UPV measured in reinforced concrete; Vc: UPV in concrete alone; Vs: UPV in steel; L: length of the course; Ls = Σ Q i: length of the course in steel.

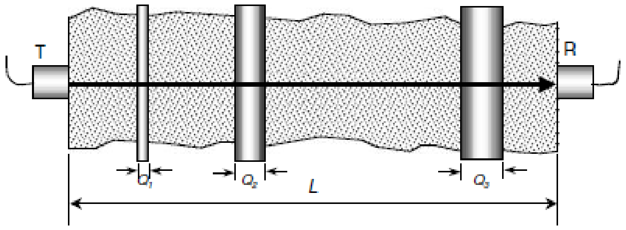

Figure 5. Reinforcements perpendicular to the direction of propagation

The values of V_C/V for different densities of reinforcements for three types of concrete are given in table 1.

Table 1. Values of V_C/V for different densities of reinforcements for three types of concrete.

L_S/L	V_C/V		
	Very poor concrete V_C = 3000m/s	Good concrete V_C = 4000m/s	Very good concrete V_C = 5000m/s
1/12	0.96	0.97	0.99
1/8	0.94	0.96	0.98
1/6	0.92	0.94	0.97
1/4	0.88	0.92	0.96
1/3	0.83	0.89	0.94
1/2	0.75	0.83	0.92

3.2. Reinforcements Parallel to the Direction of Propagation

Figure 6 shows the arrangement of the reinforcements parallel to the direction of propagation. If the reinforcement is at a distance "a" determined from the line connecting the closest points of application of the two transducers and the path length between these two transducers is L, the transmission time t is given by the following formula (Eq. 5):

$$t = \frac{L}{V_S} + 2a\sqrt{\frac{{V_S}^2 - {V_C}^2}{V_S . V_C}} \quad pour \frac{a}{L} < \frac{1}{2} . \frac{V_S - V_C}{V_S + V_C} \qquad (5)$$

The value of the ultrasonic pulse velocity in steel Vs can be determined, by sending a pulse along the axis of the reinforcement coated by the concrete. This value is generally between 5200 m/s and 6000 m/s.

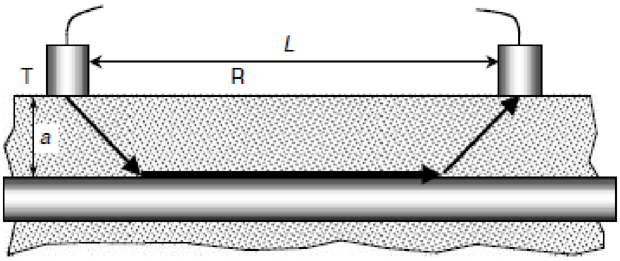

Figure 6. Reinforcements parallel to the direction of propagation

Table 2 gives the correction values to be applied to the ultrasonic pulse velocity measured in the direction parallel to the reinforcements.

Table 2. Correction values to be applied to the UPV measured in the direction parallel to the reinforcements

a/L	V_C/V = 0.90	V_C/V = 0.80	V_C/V = 0.71	V_C/V = 0.60
0	0.90	0.80	0.71	0.60
1/2	0.94	0.86	0.78	0.68
1/15	0.96	0.88	0.80	0.71
1/10	0.99	0.92	0.85	0.78
1/7	1.00	0.97	0.91	0.83
1/5	1.00	1.00	0.99	0.92
1/4	1.00	1.00	1.00	1.00

4. Measurements and Correlation UPV- Resistance

The important physical properties of materials that influence UPV are the modulus of elasticity and the density. For concrete, these properties are related to the type of aggregate, their proportions and their physical properties. The properties of cement paste are mainly linked to the initial Water/Cement ratio and the concrete's maturity. On the other hand, the strength of concrete is more linked to the Water/Cement ratio than to the type of aggregate and the proportions of aggregate and paste. Consequently, the correlations between UPV and the resistance of concrete are physically indirect, and must be established for a specific concrete mixture. Indeed, the estimate of the resistance by basing only on the UPV is not reliable for an unknown concrete.

4.1. Correlation Using Molded Specimens

The method used to vary the resistance of the specimens influences the correlation. It is therefore essential to use only one resistance variation method for a particular correlation, and it must be adapted to the required application. The correlation between the UPV and resistance is less and less reliable as the resistance of concrete increases. A correlation obtained by varying the age of the concrete is suitable for controlling the development of resistance, but for quality control it is preferable that the correlation was obtained by varying the Water/Cement ratio.

The test specimens must be prepared in accordance with the requirements of NF EN 12390-1 [17] and NF EN 12390-2 [18]. At least three specimens should be poured for each test. It is recommended to measure the UPV between the molded faces of cubic test pieces or axially by cylindrical test pieces or cores. In the case of beams, it is preferable to measure the UPV along their length in order to obtain better accuracy. For each specimen, at least three measurements should be made, between the top and the base. The difference between the times measured on each test specimen must be within ± 1% of the average value of these three measurements; otherwise, the specimen will be rejected and considered abnormal. The resistance test of the specimens should then be carried out according to the methods described in NF EN 12390-3[19].

The average UPV and the average resistance obtained from each series of three strictly identical test specimens provide the data for establishing a correlation curve.

A correlation curve established in this way only applies to test specimens made, hardened and tested in the same way, different correlation curves will be obtained for the same concretes if the cure in water is replaced by air drying.

4.2. Correlation by Testing on Concrete Cores

When correlating from core tests in a structure, it is not possible to deliberately vary the strength of the concrete. UPV tests should therefore be used to locate areas of different quality, and the cores taken from these areas will give a range of resistances. To establish the correlation, the UPV through the concrete must be used at the same locations as the cores. The UPV obtained on cores after cutting and immersion will generally be higher than those obtained before coring and it is not recommended to use them for direct correlation. The ends of the cores must be prepared for resistance testing in accordance with EN 12504-1 [20] in order to establish a correlation curve (Figure 7).

5. Factors Affecting Pulse Velocity

Several factors can affect the UPV, whether related to concrete properties or otherwise.

5.1. Influence of Porosity

The influence of the porosity of concrete on UPV has mainly been studied experimentally on cement or mortar samples containing only sand, in order to overcome the effects caused by the presence of heterogeneity of larger dimensions.

Concrete admixtures called "air entrainers" can artificially increase the porosity of the cement paste. These adjuvants were used by Punurai et al. [21], thus generating 10% of pores with a diameter of 1 mm in cement blocks. Chaix et al. [22] replaced such pores with 1 to 2 mm diameter polystyrene beads in mortar. The results show a very marked increase in the damping factor of the compression waves in the presence of such pores. This effect is all the more important when the frequency is high (above 500 kHz). Furthermore, the speed of the compression waves decreases sharply with the presence of air bubbles.

Similar results for air bubbles of the same dimensions are also observed by analytical simulations and measurements on fresh mortar still liquid, when monitoring the evolution of the material during the cure [23].

5.2. Influence of the Water/Cement ratio

The porosity of cement pastes depends directly on the W/C ratio used in the formulation. The pore size is generally much smaller than in the case of artificial porosity, and the porosity can vary from 11% to 18%.

At high frequencies (> 1.5 MHz), on blocks of cement or mortar whose W/C ratio varies from 0.45 to 0.65, measurements in compression waves show that the W/C ratio strongly influences on the damping factor [24]. On the other hand, similar measurements at lower frequencies (below 800 kHz) show that the variations in the damping factor as a function of the W/C ratio are smaller [25]. Whatever the frequency considered the UPV measurements of the compression waves show a very high sensitivity with the W/C ratio.

Figure 7. Core preparation. (a) Taking a core sample from a concrete block; (b): Preparation of the ends of the concrete core; (c): Compressive strength test of core sample.

Similar studies have been carried out on concrete containing large aggregates (D_{max} = 37.5 mm) [25,26] in the frequency band 20-800 kHz. The results are generally comparable to those obtained on cement or mortar, but due to the greater degree of heterogeneity, the gaits of the speed or damping curves with frequency present sudden variations make it more difficult to compare the results than in the case of mortar.

Whether on cement, mortar or concrete, variations in the W/C ratio strongly influence the UPV values. The variations of the damping factor are important for the higher frequencies, but are relatively weak below 1 MHz, the precision of the estimation of these damping factors must therefore be very high, which is made all the more difficult by the presence of aggregates.

5.3. Influence of Micro-cracks

The presence of micro-cracks in the mortar is studied by Aggelis and Shiotani [27,28] by introducing small vinyl plates of different dimensions (from 15 × 15 × 0.2 mm^3 to 30 × 30 × 0.5 mm^3) and at different concentrations (from 1% to 10%). The plates are randomly oriented in all directions in space. An increase in the inclusion concentration considerably increases the phase velocity and attenuation values for frequencies below 300 kHz. UPV measurements show that Rayleigh waves are much more sensitive than compression waves to this type of heterogeneity; the authors attribute this effect to the fact that the particle movement associated with the Rayleigh wave being elliptical, these waves are more sensitive to cracks or platelets oriented in all directions, while a purely compression wave will be less influenced by a plate or crack oriented along its direction of propagation.

5.4. Influence of the Saturation Rate of Concrete

The water content of the concrete represents the volume ratio of free water in the material; it can be between approximately 4 and 14%. It can also be expressed in terms of the saturation rate of the concrete, then between 0 (completely dry material) and 100% (completely saturated material), although these extreme values are never reached in practice. This saturation rate influences the UPV in concrete [29] as well as in rocks [30]. A large experimental plan was carried out to study in particular these effects of the saturation rate on different concretes [31,32]. These studies show that the variation in phase velocities with the water content is significant and does not vary linearly with the rate of saturation.

5.5. Influence of Concrete Temperature

Beyond the range of temperatures between 5 to 20°C, the influence of temperature is very important and corrections must be made in accordance with BS 1881 [33]. Table 3 gives the necessary corrections for an air-dried concrete and a water-saturated concrete.

Table 3. Corrections for UPV due to concrete temperature

Concrete temperature	Correction (%)	
	Air-Dried Concrete	Water-Saturated Concrete
60	+5.0	+4.0
40	+2.0	+1.7
20	0	0
0	-0.5	-1.0
Under -4	-1.5	-7.5

6. Conclusions

The non-destructive Ultrasonic Pulse Velocity Test consists of taking measures which do not damage the constructions. It represents a method of recognition commonly applied to building structures. It can also play an exceptional role in guaranteeing the quality of concrete and in the further development of construction technology.

The significance of the Ultrasonic Pulse Velocity Test will develop considerably in the future, because its automated measurement technology and the reduction in the size of the measuring equipment will open up entirely new applications.

An important characteristic of the Ultrasonic Pulse Velocity Test is that it can be redone in almost the same place, which makes it possible to follow changes in the properties of concrete over time.

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