Review of the ultrasonic pulse velocity
Evaluating concrete compressive strength on site

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Abstract--The main purpose of non-destructive methods applied to concrete structures; is to provide a proper evaluation of the quality of the material in its very structure, without having to trust solely to test results that do not necessarily represent the exact structure of concrete work. Among these methods, ultrasonic testing plays an important role with its convenience of use and reasonable cost. Insofar as we are primarily interested in the evaluation of the strength of concrete on-site; Commonly called the ultrasonic pulse velocity (UPV) is a comprehensive method, which provides information on both the mechanical parameters (Young's modulus) than on structural graders (compositions and densities) of the material investigated. Although there is no direct relation between the compressive strength of concrete and the ultrasonic pulse velocity; the resistance can be evaluated by establishing beforehand correlations.

This Communication aims to revisit this method emphasizing on its methodology and norms or standards that can guide its use on the assessment of the strength of concrete on site.

Keywords—ultrasonic pulse velocity, compressive concrete strength, correlations.

I. Introduction

The techniques based on the auscultation propagation of mechanical waves are widely used in the fields of metallurgy [Garnier et al. 2009]. They are derived from seismic and geophysical methods are based on the interpretation, either in time or in frequency, the wave function stored in the transmitted wave. The main techniques are: Ultrasound (U.S.), the surface waves (OS) [Hévin 1998, Hassaim 1999, Al Wardany 2005] Acoustic Tomography (TO) [Côte 1988, Sahebi 1996, Kharrat1997] Acoustic Emission (EA) and impact-Echo (IE).

II. Historic

Acoustic methods with visual inspection are the oldest forms of nondestructive testing. Sound is a means of detecting the presence of voids, cracks or delamination. In 1920, the Russian scientist Sergei Y. Sokolov Institute of Electrical Leningrad in the USSR was the first who proposed to use the ultrasonic wave velocity (UPV) to find defects in metal objects. However it was not until...
1942 that real progress was made by Firestone at the University of Michigan and independently by Sproule in England [NDT ResourceCenter].

After the Second World War, was followed by a rapid change in the instrumentation of non-destructive testing; the main objective is the detection of defaults. In response to this need techniques more sophisticated using ultrasound; eddy current, radiography ... appeared.

It was in the early 1970s with the improvement of technology, the onset of the fracture mechanics and the development of new laws to predict the growth rate of cracks in concrete under cyclic loading (fatigue) that a real and significant change occurs in the field of nondestructive testing.

III. Different acoustic technics used in nondestructive testing

For non-destructive testing of concrete (CND), methods based on the propagation of mechanical waves frequently called acoustic waves, the most used are:
- Ultrasound (auscultation sonic or ultrasonic pulse velocity UPV)
- The impact-echo
- The acoustic emission
other techniques such as seismic tomography or surface waves remain of limited use.

A. The technique of the acoustic emission
this method; differs in that it is not necessary to artificially generate elastic waves in the material. The signals detected in a non-destructive testing from the mechanical behavior of the structure under load. The material is therefore limited to the reception, often composed of several sensors to locate the source of the issue and therefore faults.

B. The technical impact-echo
this method consists in the interpretation of the frequency domain response of a structure to a shock. Its implementation is simple; the measuring unit consists of a generator (hammer or ball) and the receiver transducer. This method relies on the properties of propagation of sound waves in the concrete product due to the surface by a steel ball impact. Sizing takes place in a place with known thickness (after removal of a core of measurement), or by measuring the propagation delay between two receivers arranged one behind the other. The resonant frequency and the propagation velocity of sound waves in the concrete used to define the thickness of the concrete at the point of measurement. A receiver records the signals mechanically, which are shown in real time on a screen and can be saved for documentation. To define the thickness of a component, you must know the material properties; in this case, the speed of propagation of sound waves in the concrete. While the resonance frequency is measured by the system, the speed of propagation of sound waves is to be determined by system calibration. This control method is used to calculate the thickness of a layer available on one side (eg. Tunnel), search for voids or defects sealing (cavities) in the concrete. This technique for measuring the thickness of an element or a coating has the advantage of being extremely accurate.
C. Ultrasonic pulse velocity (UPV)

Commonly known (UPV) is a comprehensive method, which provides information on both the mechanical parameters (Young's modulus) than on structural graders (compositions and densities) of the material investigated. In the case of the ultrasonic testing of concrete, such waves are generated by piezoelectric crystals to shock excitation, also used in the receiver. These waves, which propagate undergo a series of processes, or they are attenuated and their modified speed, related to the geometrical beam divergence in the form of heat dissipation due to the viscosity of the material and diffuse through the interaction with all broadcasters they face. These diffusers are aggregates, sand grains, cracks and micro-cracks or reinforcement bars.

In the case of emission wave frequencies appropriate, the beam energy can be transferred into coherent waves transmitted as well as incoherent waves transmitted as well as backscattered waves. The general principle is to measure the velocity of the mechanical wave propagating in the concrete by transmission, this method is mainly used to detect, among other things a non-uniformity of properties of the structure, large cracks or voids resulting, for example, «honeycombs». It can also be used to determine the coefficient of elasticity or Poisson coefficient, [Zhou et al modules. 1995 Qixian Bungey and 1996, Wu et al. 1995].

IV. Ultrasonic pulse velocity commonly called UPV

A.Historical

by the early 1940s; [Powers, 1938, Obert 1939 Hornibrook 1939 and Thomson 1940] were the first to conduct extensive research on nondestructive ultrasonic technics as the method of vibration resonance frequency.

After the Second World War, research was accelerated [Carino. 2003] and the development of UPV began in England [Jones. 1948] and Canada [Leslie et al. 1949] to the stage of laboratory research it passes to the application on site; to become an essential tool for non-destructive testing, commonly used by many companies to evaluate the compressive strength of concrete in situ.

B.Principle of Operation

The UPV technic is based on the principle of the speed pulse of a compression wave transmitted through a medium and depends on the elastic properties of the medium. The principle of the UPV consists in measuring the time of propagation of a wave train between two points. The transducer produces ultrasound due to the piezoelectric properties of the materials; the electrical output energy is converted into mechanical ultrasonic energy. The device measures the time t required for the wave to reach the receiver that converts the electric signal (Figure 1). Knowing the distance from the transmitter to the receiver, it is possible to know the velocity v of the wave in the medium.
The speed $v$ of the pulse is given by the relation:

$$v = \frac{l}{t}$$  \hspace{1cm} (1)

The wavelength is usually generated by piezoelectric crystal shock excitation, also used by the receiver. The trials of measuring the propagation velocity allow to determine the elastic constant through the time of transmission of the pulse.

Longitudinal wave

$$vl = \sqrt{\frac{E(1-v)}{\rho(1+\nu)(1-2\nu)}}$$  \hspace{1cm} (2)

Transversal wave

$$vt = \sqrt{\frac{E}{2\rho(1+\nu)}}$$  \hspace{1cm} (3)

Where $vl$ and $vt$; are the longitudinal and transversal velocities, $\rho$ the density of the medium, $E$ the modulus of elasticity and $\nu$ the Poisson's ratio.

C. Devices and methodology

Industrial unit (figure 2) is composed of

- an electric generator (voltage 150 to 1000 volts) and amplifier waveguide
- a transmitting transducer
- a receiver transducer (one or more for the indirect method)
- a calibration bar
- an oscillatory to see the signal and measure the time
D. Methodology

There are 3 methods for conducting ultrasonic test:

- The transparency measurements (Figure 3 and 4) of longitudinal sound waves through a member. The transmitter and receiver are placed on the two opposite faces of the element to test. It is the most widely used method because there is maximum pulse energy which is transmitted and received so this is the most satisfactory method.

- Indirect measures or surface (Figure. 5): This method is carried out mainly when a single side of the element is accessible when it is necessary to determine the depth of a crack or the presence of multiple layers in the same element. To perform this measurement, place the transmitter and receiver to the same planar face of the element to test. The transmitter remains on the same point, whereas the receiver is moved each time by performing a measurement. Or you can work with multiple receiving transducers.

- The semi-direct measurement (Figure. 6): the transmitter and the receiver are placed on two perpendicular sides. We use this method when the whole structure is not visible. The distance between the two transducers must not be too large so that the wave is attenuated too much and do not facilitate the detection of the pulse signal.

E. Factors affecting propagation velocity

Several factors can affect the speed of propagation related to whether or other properties of the concrete.

- aggregate size and type, size, content
  Several researchers have shown that the speed pulse is affected by the type and content of aggregates. Jones 1958 reported that for the same composition and the same concrete compressive strength, concrete compound with rounded aggregates has the lowest rate of spread, the crushed aggregates by giving a higher propagation velocity value. Results of additional research [Jones 1962, 1959 Bullock and
Kaplan 1959] have shown that for the same value of resistance to compression, the concretes with the highest levels of the aggregates give the highest velocity values.

- **Type of cement**
The type of cement has no direct influence on the propagation velocity [Jones 1954]. The hydration rate differs from one to another cement and this affects the speed of propagation. As the degree of hydration increases, the modulus of elasticity also increases as well as the propagation speed.

- **The water / cement ratio**
Kaplan [Kaplan 1959] in his research work has shown that when the w / c ratio increases, the strength of concrete in compression and the value of the speed of propagation corresponding decreases assuming the same concrete composition.

- **Adjuvants**
Air-entraining admixtures do not really have an influence on the relationship between the propagation speed and the compressive strength of concrete [Jones 1954]. Other adjuvants will influence the propagation velocity approximately the same as the rate of hydration. The addition of calcium chloride for example, reduces the time of hardening of concrete and increases the value of the speed of propagation.

- **The age of concrete**
The phenomenon is similar to the development of compressive strength of concrete. Jones 18 showed that the propagation speed increases very rapidly and then stabilizes. The propagation velocity reaches its maximum value faster than the resistance. It concluded that experimental errors make it impossible to accurately assess the value of the compressive strength with precision.

- **Positioning the transducer**
The nature of the contact of the transducer with respect to the surface of the item under test has a large influence sweats value propagation velocities; improper contact may lead to erroneous propagation velocity readings.

- **Temperature concrete**
Beyond the range of temperatures between 5 to 20 °C; the influence of the temperature is very important [Jones et al. 1969] corrections must be made as recommended in BS 1881 Part 203 1986 standards.

- **The moisture condition of concrete curing**
The value of the propagation velocity for a saturated concrete is higher than for a concrete that hardens in air. Nevertheless, the influence of moisture is less important on the concrete as high resistance concretes with normal resistance.

- **Distance between transducers**
In theory the travel distance of the wave and its frequency should not delay, so there is no effect on the speed of propagation due to the nature of non-homogeneity of the concrete [Jones 1962]. RILEM 24 [RILEM, 1972] recommends the optimal distances between the following transducers:
  - 100 mm - for a concrete with a maximum dimension of the aggregates is 30 mm.
  - 150 mm - for a concrete with a
maximum dimension of the aggregates is 45 mm.

- Presence of reinforcement bars
  One of the most important factors influencing the speed pulse is the presence of reinforcing bars. The propagation speed of the steel is 1.4 to 1.7 times that of the solid concrete. Then the best way when it is possible, is to avoid testing in the place of the presence of reinforcing bars.
  When this is unavoidable it must then be corrected by correction factors affecting; that are recommended by the RILEM 23 [RILEM. 1972] and British standards.

V. Relationship compressive strength vs. UPV.

Although there is no direct physical relationship between the compressive strength of concrete and the ultrasonic pulse velocity; the resistance can be evaluated by establishing beforehand graphics curves correlating the two parameters (Figure 7).

![Graph](image)

Figure.7: example of relationship compressive strength vs. UPV

The relationship between compressive strength and the propagation speed is not unique especially as it is affected by several factors. The influence of these factors has been studied by several researchers [Sturrup et al. 1984 Anderson et al. 1981 Kaplan 1959], all have concluded that it is futile to attempt to establish a theoretical relationship between the compressive strength and the speed of propagation except if made in advance to establish correlations for the same type of concrete that is under investigation.

RILEM [RILEM. 1972] British Standard [BS 1986] and ACI American Concrete Institute [ACI. 1995] recommend developing and establishing a relationship between the velocity of propagation and compressive strength as they may be used later for in-situ monitoring of concrete.

VI. Standards and Guidelines for the testing of the UPV

Several standards and recommendations (guidelines) were developed to standardize and regulate the procedure for many nondestructive testing ultrasonic measurement of the UPV; the oldest procedure used is given by the American standard ASTM-C597-0 since 1971. Different norms and standards across countries are summarized here below:

- ASTM C-597-0, standard test method for pulse velocity through concrete
- EN 12504, testing concrete structure in part 4; determination of ultrasonic pulse velocity.
- D676-02, standard test method for deep foundation integrity of concrete by ultrasonic crosshole testing.
- ASTM C-1383 test method for measuring the P-wave speed and the thickness of concrete using the impact echo method annual book of ASTM standards vol.04.02
• IAEA guidebook on non-destructive testing of concrete structures, Vienna 2002;
• ACI 228.1R-03 ACI committee report; in place methods to estimate concrete strength.

VII. Conclusion: limitations and reliability.

Ultrasonic method is a great way to study the homogeneity of the concrete. The procedure is simple; the equipment available on the market is easy to use in the laboratory and on site. With the availability of small portable digital instruments, which are relatively inexpensive and easy to use, ultrasonic testing adds a new dimension to the quality of nondestructive testing of in-situ concrete. Since a large number of variables affect the relationship between the parameters of concrete strength and UPV, its use to evaluate the compressive strength of concrete is not recommended unless correlation tests were performed beforehand.

REFERENCES

ACI 228.1R-03: ACI committee report; in place methods to estimate concrete strength.

ACI. 1995 ACI Committee 318 Standard Building Code

AIEA: guidebook on non-destructive testing of concrete structures, Vienna 2002;


ASTM-C 1383, test method for measuring the P-wave speed and the thickness of concrete using the impact echo method annual book of ASTM standards vol.04.02

ASTM-C 597-0, standard test method for pulse velocity through concrete


D676-02, standard test method for integrity of concrete deep foundation by ultrasonic crosshole testing.

EN 12504, testing concrete in structure part 4; determination of ultrasonic pulse velocity.


[Thomson 1940]: Thomson W T., «Measuring changes in physical properties of concrete by the dynamic method», proceeding ASTM, 40, 1113, 1940.
