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Ultrasonic Pulse Velocity Evaluation of Cementitious Materials

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1. Introduction

There is a growing interest at an international level in non-destructive testing of cement based materials, such as: impact-echo, pulse-echo, ultrasonic pulse velocity, wave reflection, resonant frequency, acoustic emission and microwave adsorption methods, along with techniques measuring the conductivity and resistance of the material (Demirboga et al., 2004; Panzera et al., 2008; Trtnik et al., 2008). The pulse velocity method has been shown, for some time, to provide a reliable means of estimating properties and offers a unique opportunity for direct, reliable, quick, safe, inexpensive and non-invasive quality control of buildings and other concrete constructions damaged by earthquake, fatigue, conflagration or other catastrophic scenarios (Leslie & Cheeseman, 1949; Elvery, 1973; Bungey, 1982).

The internal structure of concrete, mortar and cementitious composites is highly complex and can be considered to be composed of (a) cement paste, which in itself is a highly complex multiphase material, (b) mineral aggregates, which are also porous composite materials and (c) the interface between paste and aggregate particles. Thus, concrete can be aptly considered a composite at a range of scales and heterogeneous at both microscopic and macroscopic levels. This complexity makes the behaviour of ultrasonic waves in concrete highly irregular, which, in turn, hinders non-destructive testing (Prassianakis & Giokas, 2003). The velocity of ultrasonic pulses traveling in a solid depends on the density and elastic properties of the material. It is thought that ultrasonic pulse velocity can often be used to assess the overall quality of a material, as well as to determine their elastic properties (Marfisi et al., 2005).

Pulses of longitudinal, elastic stress waves are generated by an electro-acoustical transducer that is held in direct contact with the surface of the concrete under test (Komlos et al., 1996). After traversing through the material, the pulses are received and converted into electrical energy by a second transducer. This common principle is expressed in somewhat different ways among the standards of various nations (see Table 1). There are also differences in how the standards discuss the factors that affect pulse velocity in cementitious composites. It is necessary to consider all factors and their correlation with physical properties, so that the measurement of pulse velocity is reproducible and exclusively dependent on the properties of the material under test (Castro & Carino, 1998).

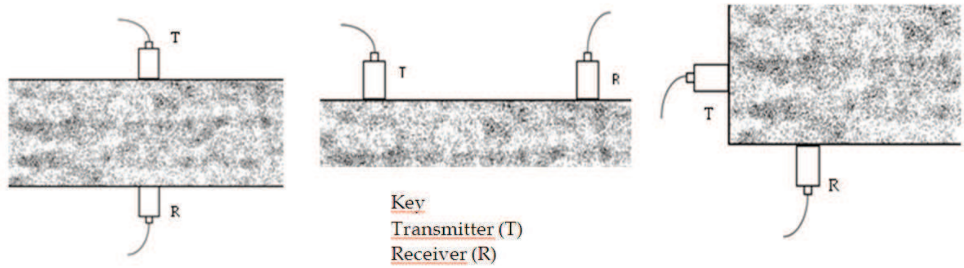
Country	Designation	Year
Begium	NBN 15-229	1976
Brazil	ABNT 18:04.08.001	1983
Bulgaria	BDS 15013-80	1980
Czech republic	CSN 731371	1981
DDR	TGL 33437102	1983
Denmark	DS 423.33	1984
Germany	Draft. Same as ISOiDIS 8047	1983
Hungary	MI 07-3318	1994
International	ISO/DIS 8047	1983
Mexico	NOM-C-275-l 986	1986
Poland	PN-B-06261	1974
RILEM	NDT 1	1972
Romania	C-26-72	1972
Russia	COST 17624	1987
Scandinavia	NT BUILD 213	1984
Spain	UNE 83-308-86	1986
Sweden	SS 137240	1983
United Kingdom	BS 12504-4: Part 4	2004
USA	ASTM C 597	1983
Venezuela	COVENIN 1681-80	1980
Yugoslavia	JUS U.Ml.042	1982

Table 1. Standards for the determination of longitudinal ultrasonic pulse velocity in concrete (Castro & Carino, 1998)[1]

The direction in which the maximum energy is propagated is at right angles to the face of the transmitting transducer; however, it is possible to detect pulses travelling through concrete in some other direction. In other words it is possible, to make measurements of pulse velocity (BS 12504-4, 2004) by placing the two transducers on either:

a. opposite faces - direct transmission (Figure 1a),
b. adjacent faces - semi-direct transmission (Figure 1b);
c. the same face - indirect or surface transmission (Figure 1c).

[1] Local standards from EU countries may have been superseded by EN 12504-4 (2004)



(a) Direct Transmission (b) Indirect or surface Transmission (c) Semi-direct Transmission

Fig. 1. Methods of propagation and receiving ultrasonic pulses (BS 12504-4, 2004)

Direct transmission is the most sensitive, and indirect transmission the least sensitive. Indirect transmission should be used when only one face of the concrete is accessible, when the depth of a surface defect or crack is to be determined or when the quality of the surface concrete relative to the overall quality is of interest. The velocity, v, is calculated from the distance, between the two transducers and the electronically measured transit time, t, of the pulse as:

$$v = \frac{l}{t} \tag{1}$$

Pulses are not transmitted through large air voids in a material. Therefore, if such a void lies directly in the pulse path the instrument will indicate the time taken by the pulse that circumvents the void by the quickest route. It is thus possible to detect large voids when a grid of pulse velocity measurements is made over a region in which these voids are located. A viscous material, such as a jelly or grease, is commonly used as a coupling agent to ensure that the vibrational energy enters the test object and can be detected by the receiving transducer (Pundit, 1990).

A number of researchers have developed theoretical models for the prediction of relationships between pulse velocity and physic-mechanical properties, such as modulus of elasticity, compressive strength, density, porosity and permeability. Other interests are focused on the correlation between pulse velocities and cement characteristics, such as water/cement ratio, aggregate particle size, hydration process and curing temperature effects. The correlation between ultrasonic pulse velocity (UPV) and the properties of cement-based materials will be presented in the following sections.

2. UPV and physical and durability properties

2.1 UPV and stiffness (modulus of elasticity)

It has been demonstrated that it is possible to measure the dynamic modulus of elasticity using established non-destructive test methods based on stress-wave propagation. The results have shown good agreement between average values of static and dynamic modulus. The dynamic values had less test variability than the static values (Castro & Carino, 1998; Vipulanandan & Garas, 2008).

Linear elastic, homogeneous and isotropic materials can be characterized by two material constants such as two elastic moduli. When there is shear deformation, the shear modulus

(G_p) controls the shear velocity. The equation relating the shear wave velocity (V_s) and shear modulus (G_p) is as follows (Leslie & Chessman 1949; Mantrala & Vipulanandan 1995):

$$G_p = (\gamma/g).V_s^2 \tag{2}$$

Where (γ/g) = mass density of the material.
If the deformation is axial (ε) and the wave velocity is controlled by the constrained modulus (M), the equation relating the constrained modulus (M) and P-wave velocity (V_p) is as follows (Leslie & Chessman 1949):

$$M = (\gamma/g).V_p^2 \tag{3}$$

For an elastic, homogenous, and isotropic material

$$M = \left[\frac{(1 - v)}{(1 + v)(1 - 2v)}\right]E \tag{4}$$

Where E= Young´s modulus of the material and ν = Poisson´s ratio
At small strain levels, the mortar system can be assumed linearly elastic homogeneous and isotropic and the dynamic Poisson´s ratio (ν_p) of different mortar composites can be found by combining Eqs (2) – (4) as follows:

$$\frac{V_p}{V_s} = \left[\frac{2(1 - v_p)}{(1 - 2v_p)}\right]^{1/2} \tag{5}$$

And the dynamic Young´s modulus (E_p) can be determined as follows:

$$E_p = \frac{(1 + v_p)(1 - 2v_p)}{(1 - v_p)}.(\gamma/g)V_p^2 \tag{6}$$

The pulse frequency used for testing cementitious materials range from about 20 kHz to 250 kHz, with 50 kHz being appropriate for field-testing of concrete. These frequencies correspond to wavelengths ranging from about 200 mm (for the lower frequency) to about 16 mm at the higher frequency (Pundit, 1990).
Hansen (1965) as cited in Nwokoye (1974) has given some practical equations for the prediction of elastic modulus of mortar and concretes. Dynamic moduli of concrete, mortar, quasi-mortar and cement past phases can be estimated from a consideration of the stiffness constant of the particular phases. For mortars in which the cement paste is considered as the matrix and sand as the particles:

$$\frac{1}{E_{ms}} = \frac{1}{2}\left(\frac{K_p}{E_p} + \frac{K_s}{E_s}\right) + \frac{1}{2}\left(\frac{1}{K_pE_p + K_sE_s}\right) \tag{7}$$

where K_p and K_s are volume fractions of cement paste and sand respectively and E_{ms} is the modulus of elasticity of mortar.
For concrete in which mortar is considered as the matrix and regular aggregate as the particles:

$$E_0 = \left(\frac{1}{\frac{1-\alpha}{E_{ms}} + \frac{\alpha}{E_a}} \right) \qquad (8)$$

Where E_0 is the elastic modulus of concrete, E_{ms} is the elastic modulus of mortar, E_a is the elastic modulus of aggregate, α is the volume fraction of coarse aggregate and β is the volume fraction of fine aggregate (β = 1- α).

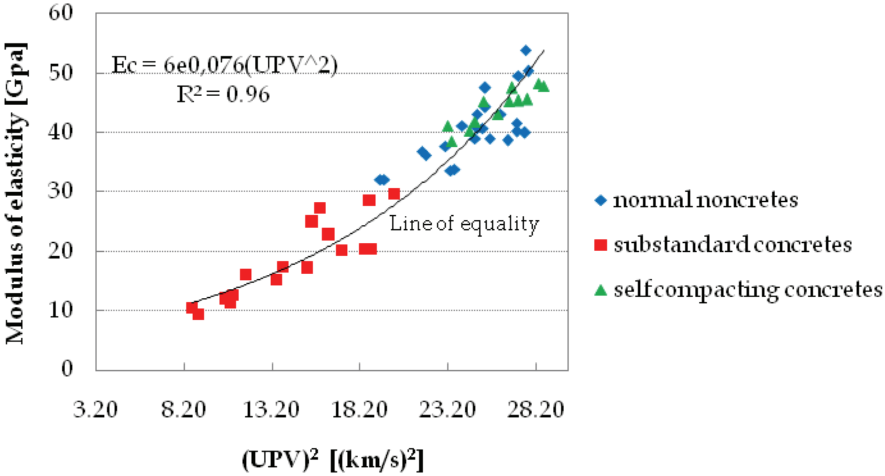


Fig. 2. Relationship between UPV and E_s (Yildirim & Sengul, 2011)

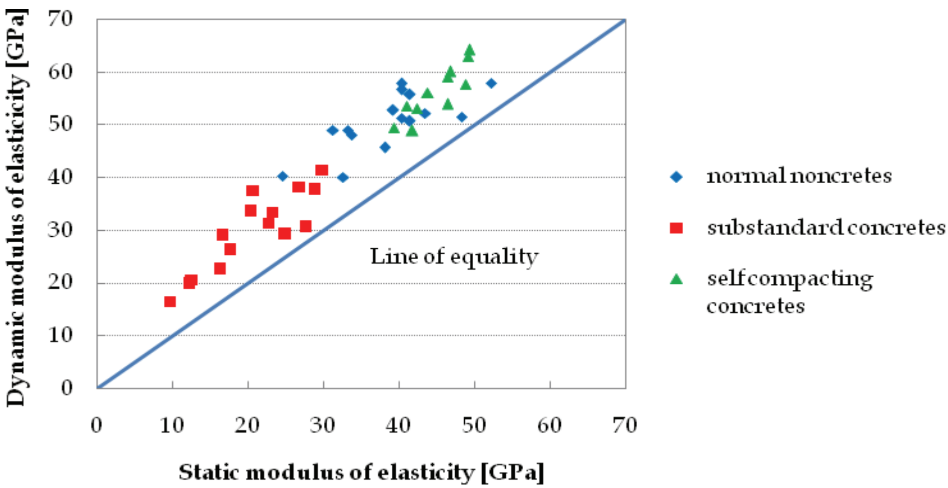


Fig. 3. Relationships between static and dynamic modulus of elasticity (Yildirim & Sengul, 2011)

Yildirim and Sengul (2011) investigated the effects of water/cement ratio, maximum size of the aggregate, aggregate type, and fly ash addition on the dynamic modulus of elasticity of low quality concrete with water/cement ratios close to 2.2. A strong relationship was obtained between the static modulus of elasticity and ultrasound pulse velocity (see Figure 2). The relationship indicates that the ultrasonic pulse velocity measurements can be used also for estimating the static modulus of elasticity of substandard concretes in existing structures where taking out cores from the structural elements is not preferred due to very low concrete strength or small dimensions of the elements. Figure 3 shows the correlation between static and dynamic modulus of elasticity. These results indicate that the dynamic modulus values are, approximately 30% higher than the static modulus obtained from compressive testing. The reason behind such a result may be that, since ultrasonic test is conducted at low stress levels, the test results more closely resemble an initial tangent modulus of the material (Yildirim & Sengul, 2011).
Trtnik et al. (2008) presented the relationships between V_p (UPV) and E_{stat}, E_{dyn} and G (Figure 4). Despite the dynamic modulus being higher than the static modulus, they exhibited the similar trends.

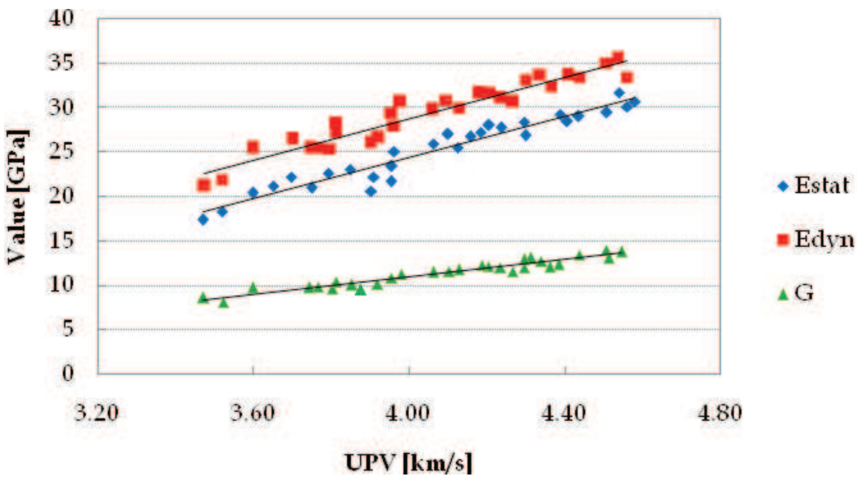


Fig. 4. Relationships between UPV and E_s, E_d and G (Trtnik et al., 2008)

2.2 UPV and strength

The ultrasonic pulse velocity in cement-based materials depends mainly on its elastic modulus and, since the latter is closely related to mechanical strength (how is elastic modulus related to strength, something can be stiff and weak (e.g. chalf)) or stiff and strong (e.g. carbon fibre), it is natural do believe the pulse velocity can be also correlated to compressive strength. The correlation, however, is not unique, but rather depends particularly on the mix proportions, cement type and type of aggregate used (Neville, 1996; Trtnik et al. 2009). Therefore, the UPV may be used to estimate compressive strength as long as a calibration curve exists for each assessed material (Mandandoust et al., 2010).
Numerous data and correlation relationships between the strength and pulse velocity of concrete have been presented and proposed. Galan (1967) reported a regression analysis to

predict the compressive strength of concrete based on acoustic characteristics such as UPV and the damping constant. Rajagopalan et al. (1973) reported a correlation between the UPV and compressive strength of concrete for some typical mixes. This particular study presented simultaneous measurements of pulse velocity and compressive strength made on 150 mm cubes at different ages from 1 to 28 days, indicating a linear relation between strength and velocity. Lin et al. (2003) carried out experiments to establish mathematical models for predicting concrete pulse velocity based on aggregate content and water–cement ratio. Tharmaratram & Tan (1990) provided an empirical formula of the combined UPV and ultrasonic pulse amplitude. Demirboga et al. (2004) found an exponential relationship between compressive strength and UPV for mineral-admixtured concrete. The equation most commonly used is (Trtnik et al. 2009):

$$S = a.\exp(b.V_p) \tag{9}$$

where *a* and *b* are empirical parameters determined by the least squares method. Table 2 presents some relationships between concrete compressive strength *S* and the ultrasonic pulse velocity of longitudinal waves V_p, together with the coefficients of determination R^2.

Equation	R^2	References
$S = 1.146\exp(0.77V_p)$	0.80	Turgut (2004)
$S = 1.19\exp(0.715V_p)$	0.59	Nashn't et al. (2005)
$S = 8.4 * 10^{-9}(V_p * 10^3)^{2.5921}$	0.42	Kheder (1999)[A]
$S = 1.2 * 10^{-5}(V_p * 10^3)^{1.7447}$	0.41	Kheder (1999)[B]
$S = \exp[(-3.3 \pm 1.8) + (0.0014 \pm 0.0004)(V_p * 10^3)]$	0.48	Rio et al. (2004)

[A]For wet concrete, [B]For dry concrete

Table 2. Relationships between concrete compressive strength and ultrasonic pulse velocity (Trtnik et al., 2009)

It can be seen from Table 1 that the coefficients of determination (R^2) are low because the concrete composition was not taken into account or, in other words, different concrete compositions were compared at a time. That is the reason why the exponential curve is also broad in Fig. 5. In fact, it is well known that many parameters or cement paste characteristics that influence the concrete strength also influence pulse velocity, though not necessarily in the same way or to the same extent (Popovics, 2007). The effect of different composite parameters on UPV results will be treated in Section 3. The results performed by Bernardo (2003) as cited in Trtnik et al. (2009) indicated a 40%increase in UPV measured after three years. The increase in the compressive strength during the same period is much higher, more than 500%.

Keating et al. (1989) investigated the correlation between UPV and strength for slurries often used in cementing oil well casings, where temperatures do not exceed 50 °C. It was shown that there is a correlation at atmospheric pressure, between pulse velocity and cube strength for the first 24 hours after mixing. A lower bound curve can be used to predict initial set and waiting on cement time, from pulse velocity (Fig. 6). The initial pulse velocity of about 1580m/s exhibited a relatively stable plateau region during the first two hours after mixing but after a period when it became possible to strip the cubes from their moulds and test them, the pulse velocity increased relatively rapidly for period up to about four hours and then at a progressively slower rate of increase for the remainder of the test. During this period the cubes showed a steady rate of increase in strength. After six hours the pulse velocity ranged from 1850 m/s to 2000 m/s with cube strengths of about 2.4 MPa while at 24 hours the range was from 2200 m/s to 2600 m/s with cube strengths of about 12 MPa.

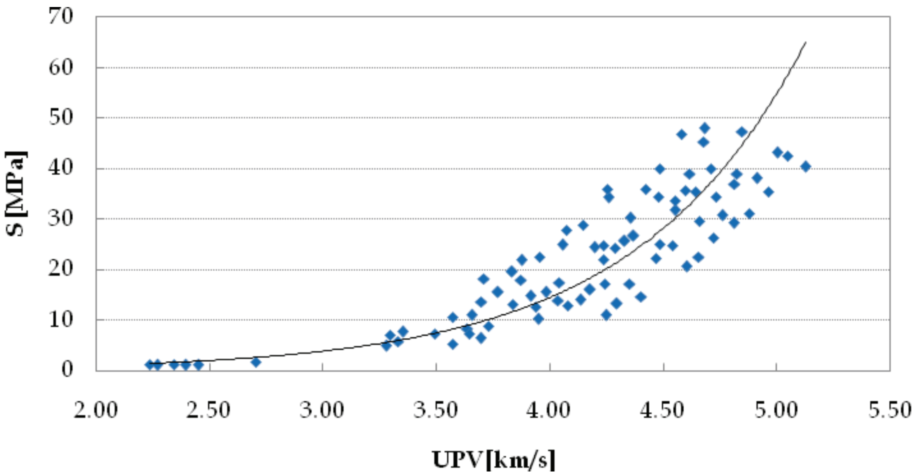


Fig. 5. Relationship between UPV and strength (Trtnik et al., 2009)

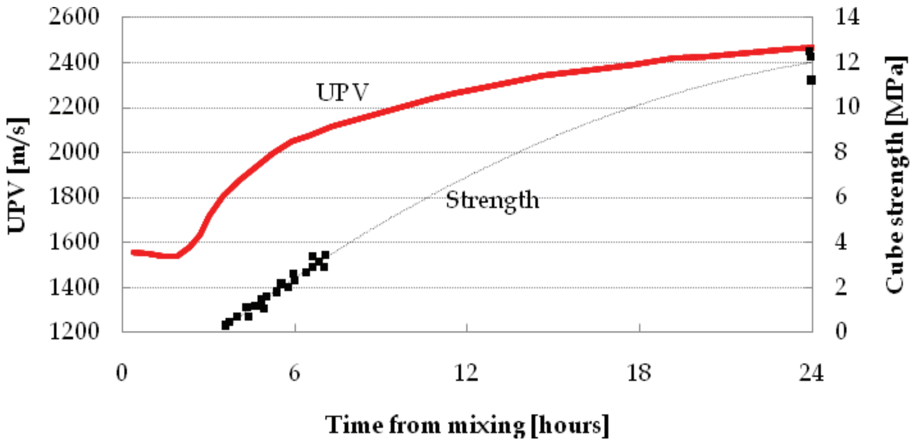
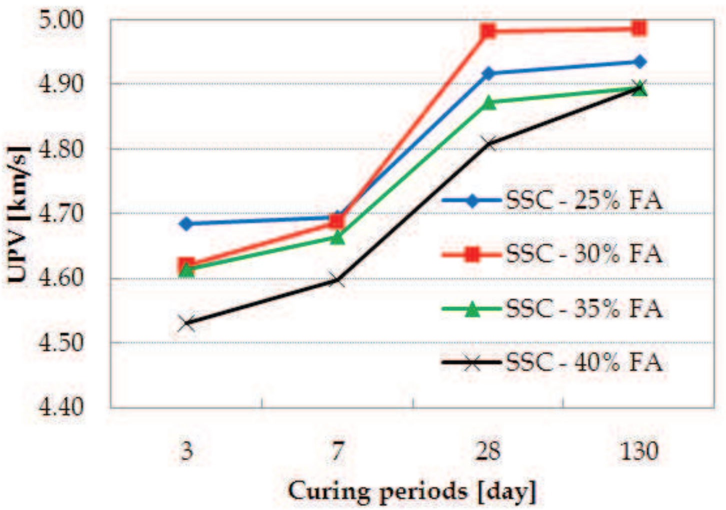
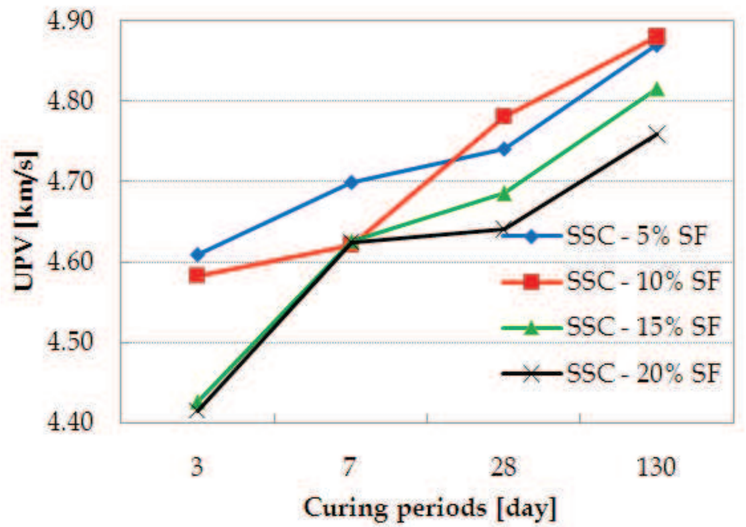


Fig. 6. Comparison between pulse velocity and cube strength at ages between 0 and 24 hours after mixing at 20 °C (Keating et al. 1989)

Ulucan et al. (2008) investigated the effect of silica fume (SF) and fly ash (FA) as mineral admixtures replacing Portland cement (PC) in self-compacting concrete (SCC). It can be seen from Fig. 7a that the UPV values decreased with increasing FA replacement of PC in SCCs at 3 and 7 days, while SCC containing 30% FA replacement had the highest UPV values at 28- and 130-day curing periods. The UPV values increased with increasing curing period at all levels of FA replacement in SCCs. The UPV values of SCCs containing FA were higher than those of SCCs with SF replacement at all levels of replacement for all curing ages (see Fig. 7b), indicating the filling and packing capacity of FA particles. The correlation between UPV and compressive strength is also exponential for SCCs containing both FA and SF (Fig. 8). However, constants for each pozzolanic material were different for each level of replacement of PC in SCCs.

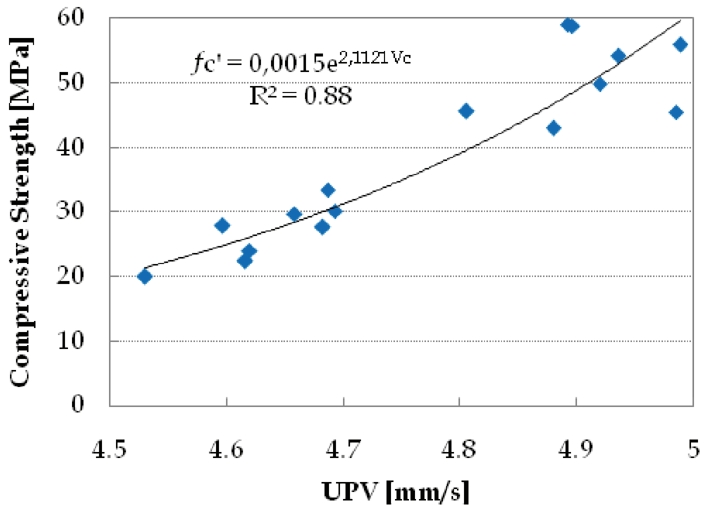


(a)

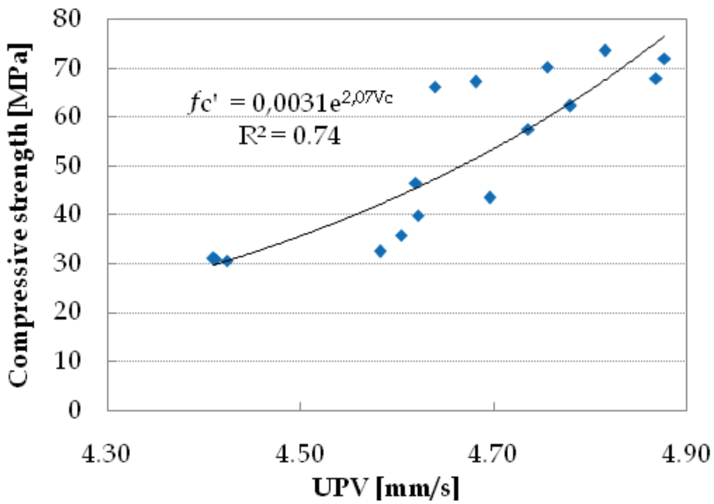


(b)

Fig. 7. UPV results for SCC with FA (a) and SF (b) for different curing periods



(a)



(b)

Fig. 8. Correlation between compressive strength and UPV for SCC with FA (a) and SF (b) (Ulucan et al., 2008)

Dmirboga et al. (2004) investigated the addition of 50%, 60% and 70% of FA as a replacement of PC. Both compressive strength and UPV were very low for all replacement levels at an early age of curing. However, with the increase of curing period, both compressive strength and UPV of all the samples increased, which confirm the findings of Ulucan et al. (2008).

Ikpong (1993) stated that the introduction of a pozzolanic material into concrete affect both the compressive strength and pulse velocity along the same direction. A unit volume of cement contributes more to the strength and pulse velocity through the concrete than does an equivalent volume of the ash. The primary products of hydration formed by the reaction between cement and water account for a greater proportion of each of these three quantities than do the secondary products of hydration resulting from the pozzolanic reaction involving the ash (Ikpong, 1993).

Mohammed (2011) studied the fresh and hardened properties of concrete containing crumb rubber (rubbercrete) as a replacement of fine aggregate. The utilization of the crumb rubber from scrap tires as a sustainable building materials in the construction industry help to preserve natural resources and maintain the ecological balance. The UPV values of the rubbercrete decrease with an increase in the percentage of the crumb rubber content and decreases with an increase in the water/cement ratio. The results also revealed that the UPV values increase as the curing age increases (Mohammed, 2011).

Other authors (Kewalramani & Gupta, 2006; Hola et al., 2005 and Trtnik et al., 2009) compared artificial neural networks and multiple-regression analysis to predict concrete compressive strength based on UPV and weight of concrete. They concluded that the prediction performed using ANN has a better degree of coherency with experimentally evaluated compressive strength than multiple-regression analysis.

Trtnik et al. (2009) studied the influence of aggregate content, nominal maximum aggregate size, type and shape of aggregate, and also the type of cement, initial concrete temperature, environmental temperature, and water–cement ratio on the strength–velocity relationship. They observed that the characteristics of the aggregate are very important to assess the compressive strength of concrete based on the measurement of ultrasonic pulse velocity. Therefore they employed some characteristics of aggregate (amount, nominal maximum size, type and shape) and UPV as input parameters to build an ANN model to accurately predict concrete compressive strength (Trtnik et al., 2009).

Despite the results presented above, some other authors did not find good correlation between strength and UPV for cementitious materials (Popovics & Rose, 1994; Qasrawi, 2000; Turgut & Kucuk, 2006; Panzera et al, 2008). The prediction of cementitious materials strength based on UPV technique depends not only on their constitution but also on the manufacturing process, which can occasionaly be a difficult and unreliable task (Zarandi, 2008). Calibration may be also an issue.

The factors influencing calibrations are so many that even under ideal conditions with a specific calibration it could be unlikely to achieve 95% confidence limits of better than ±20% for an absolute strength prediction of insitu concrete (Mandandoust et al., 2010).

2.3 UPV and porosity, permeability & density

Deterioration of concrete is generally caused by penetration of aggressive agents –sulfates, nitrates, chlorides, water, frost, CO_2 – into the material interior. The kinetics of reaction of concrete with those agents, hence its durability, is essentially determined by the transfer properties of the cover, i.e. the first few centimeters below the surface of the structure (Goueygou et al, 2009; Lafhaj et al., 2006).

The theoretical relationship between ultrasonic propagation and material durability parameters is based on a simple model proposed by Yaman et al. (2002). The longitudinal and shear wave velocities are related to the modulus of elasticity and density by well-known formulas (10) (Popovics, 2007):

$$V_p = \sqrt{\frac{E}{\rho}.\frac{1-v}{(1+v)(1-2v)}} \quad V_s = \sqrt{\frac{E}{\rho}.\frac{1}{2(1+v)}} \tag{10}$$

Next, the relationship between Young's modulus and porosity p is taken in the form of a power law (Popovics, 2007).

$$E = E_0(1-p)^c \tag{11}$$

where c is an empirical fitting parameter and E_0 is the Young's modulus of the material at zero porosity (in what follows, index "0" will refer to the zero-porosity material). As density is related to porosity by:

$$\rho = \rho_0(1-p) \tag{12}$$

and neglecting the influence of porosity on Poisson ratio, i.e. $\nu = \nu_0$ for a given value of water content, insertion of Eqs. (11) and (12) into Eq. (10) yields:

$$\begin{aligned} V_p &= V_{p_0}(1-p)^a \\ V_s &= V_{s_0}(1-p)^a \end{aligned} \tag{13}$$

Where, $V_{p_0} = \sqrt{\frac{E_0}{\rho_0}.\frac{1-v_0}{(1+v_0)(1-2v_0)}}$, $V_{s_0} = \sqrt{\frac{E_0}{\rho_0}.\frac{1}{2(1+v_0)}}$ and $a = \frac{c-1}{2}$

For low porosity values, Eq. (13) can by approximated by the following linear relationships:

$$\begin{aligned} V_p &= V_{p_0}(1-bp) \\ V_s &= V_{s_0}(1-bp) \end{aligned} \tag{14}$$

According to Shkolnik et al. (1997), parameter b is related to Poisson ratio at zero porosity by:

$$b = 15\left(\frac{1-v_0}{7-5v_0}\right) \tag{15}$$

Finally, the porosity (*p*) and permeability (*k*) relationship is derived from a simple model, assuming that for fluid flow, the system of open pores is equivalent to a set of parallel circular channel of diameter d directed along the macroscopic fluid flow (Udegbunam et al., 1999):

$$k = \frac{pd^2}{32} \tag{16}$$

Combining Eqs. (14) and (16), a linear relationship between permeability (*k*) and UPV can be derived:

$$k = \frac{d^2}{32b}.\frac{\Delta V_{p,s}}{V_{p,s_0}} \tag{17}$$

Where $\frac{\Delta V_{p,s}}{V_{p,s_0}}$ corresponds to the variation of UPV of longitudinal or shear wave relative to the zero-porosity value. Eqs. (13), (14) and (17) represent the theoretical model relating UPV with porosity and permeability.

The ultrasonic test has been used for nondestructive durability assessment to chloride ion penetration (Shkolnik et al., 1997; Udegbunam et al., 1999; Lafhaj et al., 2006). Three ranges of saturation were considered: full saturation (FS) when the water content is more than 85% of the fully saturated specimen; partial saturation (PS) when it is in between 45% and 55%; dry (D) when the saturation is less than 10%. The variation of ultrasonic parameters can be observed in Fig.9. Pulse velocity decreases with porosity and permeability, and it increases with water content. Such trends are in accordance with works published by other researchers (Winkler & Nur, 1982; Ohdaira&Masuzawa, 2000; Vergara et al., 2001). The dependence of permeability on porosity and water content is very significant. As a matter of fact, permeability does not depend only on porosity but also on tortuosity, specific surface, pore size distribution and connectivity of pores.

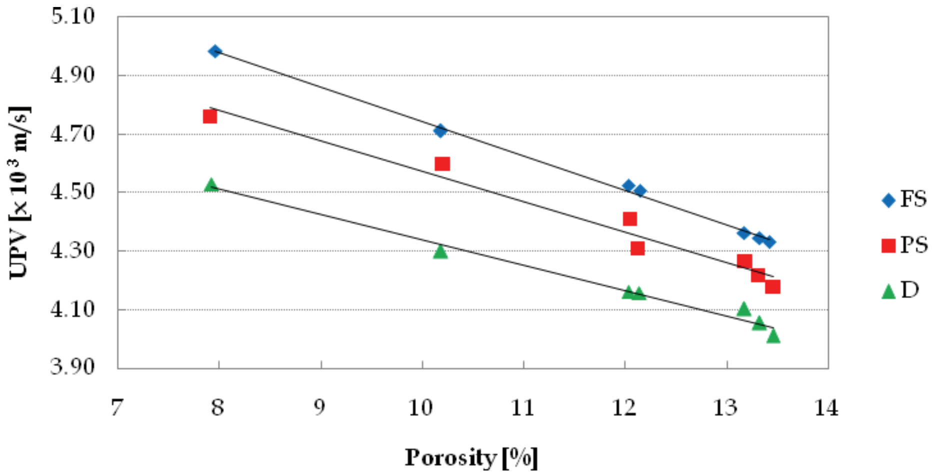
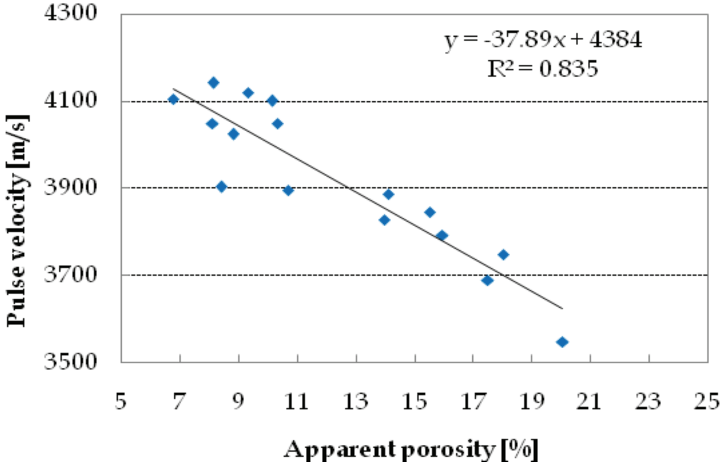


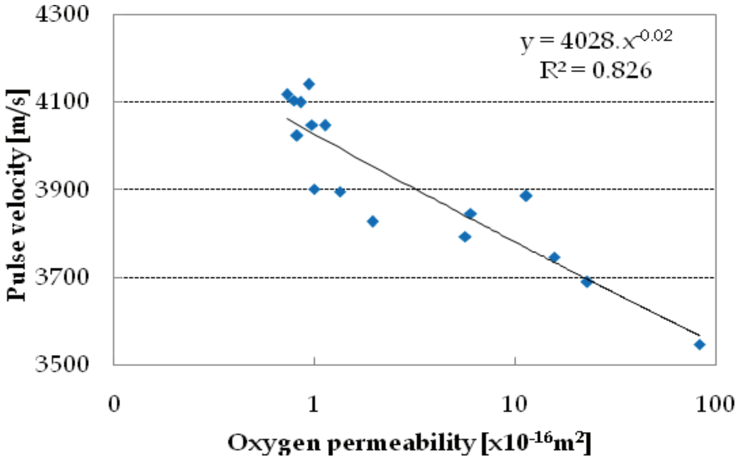
Fig. 9. Variation of UPV versus porosity (Lafhaj et al., 2006)

Panzera et al. (2008) investigated the effect of UPV of compacted cementitious composites based on ordinary Portland cement (OPC) and silica particles with a low water/cement ratio. The results reveal a significant correlation between the UPV and porosity (Fig. 10a) and oxygen permeability (Fig. 10b). A decrease of the pulse velocity corresponds to an increase of porosity and oxygen permeability, which confirms that a region of low compaction, voids or damaged material is present in the composites and leads to a reduction in the calculated pulse velocity.

A linear correlation between UPV and bulk density was found represented by the equation y = 1506.9x + 541.7 (R^2 = 88.69%), where y is the pulse velocity and x the bulk density. As observed in Figure 11, the higher the pulse velocity the higher the bulk density of the cementitious composites (Panzera et al 2008).



(a)



(b)

Fig. 10. Correlation plot between the apparent porosity (a) and (b) permeability versus UPV (Panzera et al., 2008)

3. Influence of paste / concrete parameters on UPV

As mentioned in section 2.2, several parameters affect strength of cement-based materials and consequently the UPV results. The following sections cover the most common parameters studied with UPV.

3.1 UPV and water content in cementitious composites

Ye et al. (2004) studied concretes with three different water/cements (w/c) ratios, 0.40, 0.50 and 0,55, and concluded that the mixes with lower w/c had higher values of UPV, which

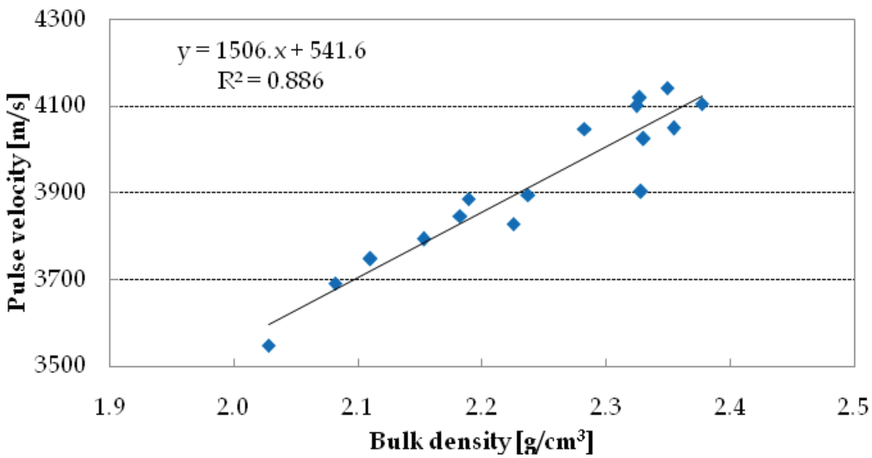


Fig. 11. Correlation plot between the bulk density and the pulse velocity (Panzera et al., 2008)

could be associated with higher amount of solids in those mixes (Fig. 12). In addition, mixes with lower w/c had more aggregate content, which also increases the pulse velocity. Some research (Trtnik et al., 2009; Madandoust, 2010) have pointed out that the influence of w/c on UPV results is more pronounced at later ages of hydration, when the volume of capillary pores is reduced. During the first three days of hydration, the ultrasonic velocity is significantly low due to the large amount of capillary pores, so that the sensitivity to w/c alterations is not noticed.

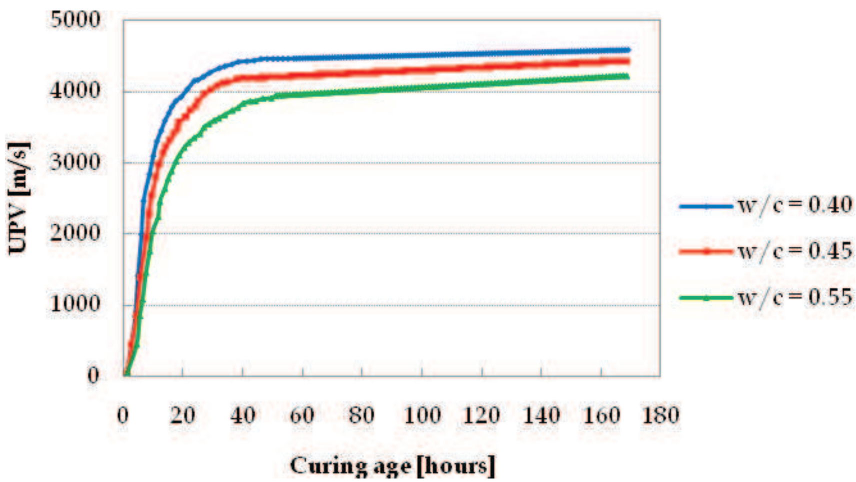


Fig. 12. Effect of the w/c ratio on UPV (Ye et al., 2004)

It is important to differentiate the effect of water content on UPV results. Mixing water, usually described in terms of w/c ratio, usually reduces UPV results as described in the last paragraph. However, the amount of water present in the samples subjected to testing (i.e. cement paste or concrete moisture) has a different impact on pulse velocity. Ohdaira (2000) and Bernardo (2003) found that moisture content helps the propagation velocity in concrete. On the other hand, it affects compressive strength negatively. So, such dissimilarities may create ambiguity in the interpretation of UPV results (Li, 2004). Lajhaf (2006) summarizes as follows: for a given value of moisture, a significant decrease of velocity is observed with increasing porosity. As an example, the reduction of velocity for the fully saturated material is about 15% when porosity increases from 8% to 13.5%. On the other hand, for a given value of porosity, velocity increases with water content, which was also confirmed by Ohdaira and Masuzawa (2000). According to Yaman et al. (2001, 2002), the UPVchanges between the dry and the saturated state because moisture changes the shape of capillary pores, which significantly affects the mechanical properties of concrete. The shear wave appears to be less sensitive to water content than longitudinal wave velocity, especially when comparing partially (PS) and fully (F) saturated samples.

In general, the change of UPV response with water content opens new possibilities of studying the hydration process and hence to develop hydration models to cement-based materials.

3.2 UPV and cement hydration

UPV may be a valuable tool to assess the hydration of cementitious materials, including the early stages when the paste is not set. The determination of the initial setting of cement, for example, still relies on standard tests like the Vicat Neddle which cannot monitor the hydration continuously and often do not represent the characteristics of concretes (Trtnik, 2008). Therefore it makes sense to search for alternative methods to follow both the initial and later stages of hydration, such as those based on ultrasonic waves.

Keating et al. (1989) studied the hydration of oil well cement slurries using UPV and observed three stages as times elapsed after mixing: an initially constant regime, a rapidly increasing regime and a much more slowly increasing or almost constant regime. Later on, several other researchers (Popovics et al. 1993; Reinhardt et al., 2000, 2004; Lee et al. 2004, Trtnik, 2008, Zhang et al., 2009) have found similar patterns in mortar and concrete, which can be generalized as in Fig 13.

At the early stages of hydration, when the paste is not set, UPV is governed by the water/air phase in the cement paste, and the air bubbles present in the water acts as the dominant factor that determines the UPV (Ye et al., 2004). Stage 1 represents this stage, when increased tortuosity of the pore or air-filled space due to the formation of hydration products may even cause slight decrease in UPV (Lee et al., 2004). At very early ages in Stage 1, the presence of aggregates does not influence the pulse velocity, given that ultrasonic waves propagate through the phase of viscous suspension. Hence, mortars or concretes with same w/c will have approximately the same UPV results.

Stage 2 begins when there is a minimum quantity of hydration products filling the pores so the connection of particles leads to clusters that form a percolating solid network. Then, this step is marked by a switch of propagation path of ultrasonic pulse from the liquid to the solid phase, with a consequent rise in UPV. It is noticed that beyond this stage the influence of the solid phase becomes dominant instead of air bubbles on the UPV (Ye et al. and Lee et al., 2004). Finally, when all the solid phase was connected, the slow increase of the UPV followed the evolution of the total solid fraction (Step 3).

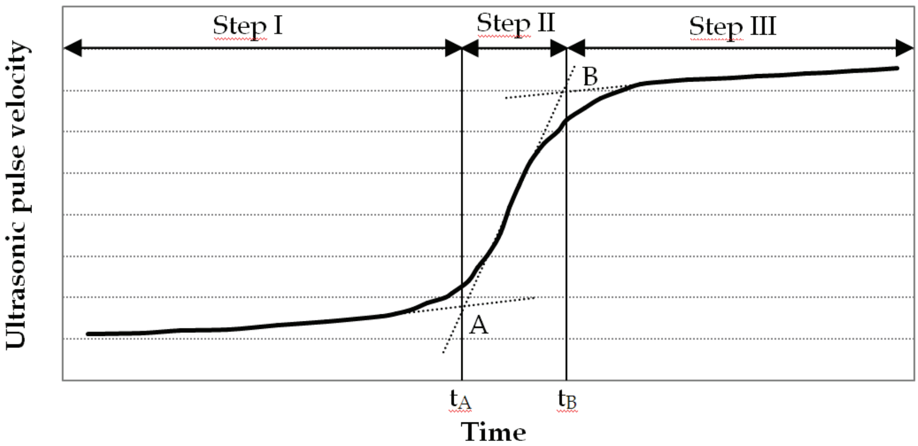


Fig. 13. Schematic representation of typical evolution of UPV in cement pastes (Lee et al., 2004)

Unlike Stage 1, the UPV profiles at later ages (Stages 2 and 3) have different shapes depending on the concrete mixtures. In other words, not only the w/c of the mixes but also the retarding effect of pozzolanic materials and the volume of coarse aggregates (which have higher stiffness than cement paste) affect the shape of the UPV with time curve.

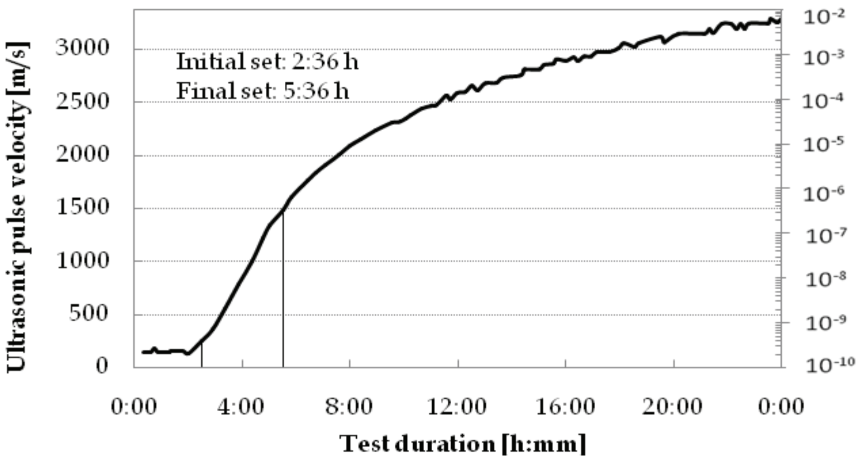


Fig. 14. Illustration of the beginning and end of setting for a mortar with CEM II 42.5 N and w/c = 0.6 (Reinhardt and Grosse, 2004)

It appears that both the onset and offset time of Stage 2 are closely related to setting of cement paste. Some authors (Reinhardt and Grosse, 2004; Chen et al., 2010) are convinced that the beginning of Stage 2 when the UPV transforms from a flat increase to a sharp one corresponds to the initial setting of cement pastes. Chotard et al. (2001) states that the duration of its sharp increase corresponds to the cement stiffening process and that the beginning of Stage 3 is when the cement skeleton approaches its final stiffness, which is in accordance with results of Zhang (2009). Reinhardt and Grosse (2004), however, points out that the final setting is still under discussion and that a practical experience shows that the velocity of 1500 m/s could define it. This could be the case for curves without a clear step transitions, as in Fig. 14.

3.3 UPV and curing conditions

It is well known that the propagation velocity of ultrasonic pulse increases with the age of the concrete. This final section shows that the increase of UPV results with curing time is related to the change in the gel/space ratio that takes place with paste hydration. Since the pulse velocity through voids is less than that through solid matter, the greater the gel/space ratio (which increases with time) the lower the volume of pores and the greater the velocity of pulses propagated through concrete (Ikpong, 1993). Due to the changes of the structure with the age of cementitious materials, the standards recommend that changes in the properties which occur in time be determined by repeated measurements of pulse velocity at different ages, but always using the same transducers in the same position (Komlos et al. 1996).

Curing time will affect the UPV results; the curing regime may also play an important role. Kheder et al. (2003) studied mortars cured either in water or submitted to accelerated curing according to the BS 12504-4 (2004) method (20 hours water bath at 55°C). It has been found out that samples submitted to accelerated curing provided better correlation between strength and density and between strength and UPV.

Gesoglu (2010) studied concretes incorporating metakaolin and silica fume. Samples were either cured in water at 23°C and or steam cured at 70°C for 17 hours. Pulse velocity was determined at 1, 7 and 28 days. For the 1-day measurements, the steam cured concretes had slightly greater UPV values than the water cured concretes, in spite of a marked difference seen in the compressive strength. But in general, it has been concluded that there was no remarkable difference in the UPV values of the steam cured and water cured concretes for all testing. Krishna Rao et al. (2010) also has found no significant differences between UPV results from concrete samples subjected to membrane curing and conventional water curing. On the other hand, Yasicioglu et al. (2006), has shown that self compacted concrete cubes provided best UPV results at all ages after curing in water at 20°C, when compared to cubes sealed (to prevent moisture loss) or air cured. This is in accordance to later results obtained by Tanyidizi (2008), which indicated that the highest compressive strength and ultrasonic pulse velocity values are obtained from water cured specimens followed by the sealed and air cured specimens regardless of the concrete types.

Not all authors agree on which curing method provides better UPV results (and this may depend on the material studied). However, there is a general agreement that the correlation between physical properties with UPV is much improved when all samples are cured the same way, irrespective of the method used (Kheder et al., 2003).

3.4 UPV and aggregate particle size and content

The presence of aggregate in cementitious composites affects the compressive strength, pulse velocity and relation between the two properties. Therefore the influence of aggregate is very important and cannot be neglected for accurate prediction of compressive strength of concrete based on ultrasonic pulse velocity (Trtnik, 2009). Researchers have found that for the same strength level, concretes with the highest aggregate content will probably have the highest pulse velocity (Crawford, 1997; Trtnik, 2009). Berriman et al. (2004) has shown a strong positive linear correlation between aggregate content in concretes and speed of sound. Therefore the amount of aggregate does not affect UPV and strength to the same degree. In some cases, the higher aggregate content can cause an increase in the UPV results and at the same time decrease in compressive strength, which will depend on the mix design (Trtnik, 2009). Considering concrete as a two-phase composite material (aggregates plus cement paste), the increase of UPV with the increase of aggregate content can be represented as in Eq. 18 (Ye, 2003):

$$\frac{1}{UPV_{CONC}} = \frac{V_{CEM}}{UPV_{CEM}} + \frac{V_{AGG}}{UPV_{AGG}} \tag{18}$$

where V_{cem} and V_{agg} are the volume percentages of cement paste and aggregate in the concrete, respectively and UPV_{cem} and UPV_{agg} are the longitudinal ultrasonic velocities of the cement paste and aggregate, respectively.

Trtnik (2009) has carried out a comprehensive study of the influence of the aggregate content, type, shape and size on the determination of strength using ultrasonic pulse velocity. It has been concluded that:

a. Aggregates with low pulse velocity reduce both the strength and UPV of concretes, when compared to aggregates with high pulse velocity;
b. For the same UPV level, mixtures with the lowest and the highest nominal aggregate size have the highest and the lowest compressive strength S, respectively.
c. At the same UPV level, a mixture with the rounded aggregate grains has lower compressive strength than mixture with crushed aggregate shape, which can be explained by weaker contact between aggregate grains and cement paste in the case of rounded aggregate grains, leading to a reduction in the concrete strength.

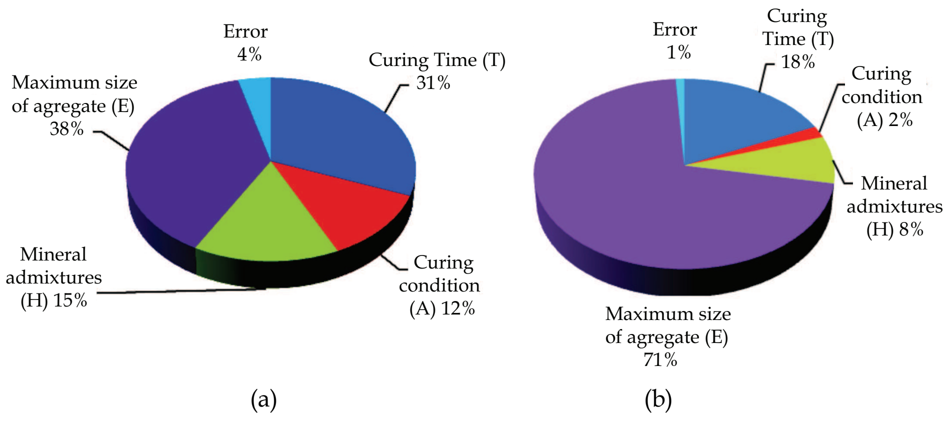


Fig. 15. The effect of experimental parameters on (a) ultrasonic pulse velocity and (b) compressive strength of lightweight concrete (Tanayidizi and Coskun, 2008)

Tanyidizi and Coskun (2008) used the analysis of variance (ANOVA) method to study the level of importance of four parameters – maximum size of aggregate, curing conditions,

mineral admixtures and curing time – on UPV and compressive strength of lightweight concrete. The results were summarized with the pie charts of Fig. 15. It is possible to see that the maximum size of aggregate is the main parameter governing both UPV results and compressive strength, being more significant for the first.
Despite the general agreement on the effect of the amount of aggregates on the correlation between UPV and strength, it is important to note that variations in the fine/coarse aggregate ratio may not affect the UPV – strength correlation (Lin et al., 2003; Madandoust et al., 2010), as shown in Fig. 16.

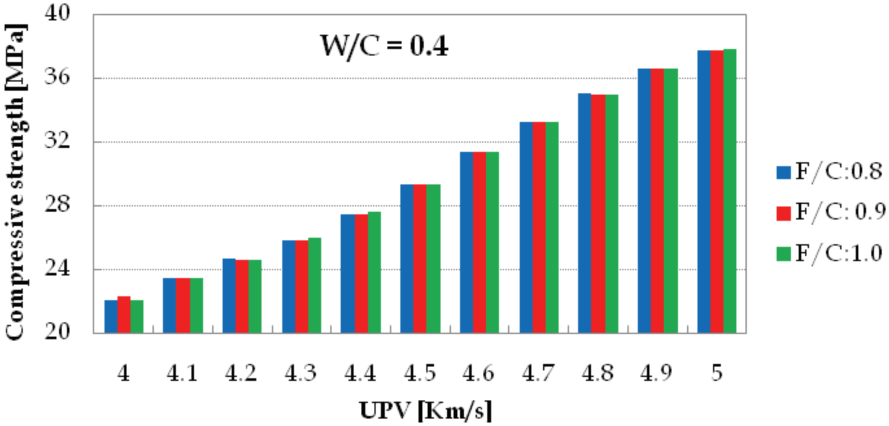


Fig. 16. Variarion of concrete compressive strength vs. UPV for different fine/coarse (F/C) aggregate ratios. Samples with w/c = 0.4 (Madandoust, 2010)

4. Special applications of UPV in cementitious composites

The objective of this section is to show a few practical examples of the utilization of ultrasonic pulse velocity as a non-destructive characterization technique for cementitious composites. It obviously does not cover all applications, but rather gives an overview of special or novel systems to where UPV can be employed. UPV has been largely used on the assessment of the uniformity of concrete, as well the detection of defects in concrete structures. The non-uniformity is indicated by the variation of the pulse velocities obtained from different points (Komlos et al., 1996). However, other examples below show that the application of this non-destructive technique goes beyond the original idea of detection of large voids or cavities in structural concrete.
UPV has been used to evaluate the strength of concrete exposed to elevated temperature. Results have shown the feasibility of using UPV for evaluation of the residual strength of fire-damaged concrete structures. UPV appears to be a qualitative (rather than quantitative) technique for determination of fire-damage in structures affected by fire (Cioni et al. 2001, Yang et al., 2009). A modified UPV test proposed by Colombo and Felicetti (2007) proved to be more effective to assess buildings affected by fire.
Lee et al (2004) used UPV to assess the early properties of high-performance concrete (HPC), which usually have a low water-to-cementitious materials (w/cm) ratio and also employ various chemical and mineral admixtures. HPC may be quite different from those of

ordinary concrete. An ultrasonic monitoring system has been used to successfully measure the UPV of both mortar and concrete beginning immediately after mixing. This method proved to be advantageous over the conventional method of conventional setting tests, as it could be conducted directly on concrete rather than on standard pastes that do not represent the rheology of HPC.

Shotcrete is employed in many situations, in particular for concreting in difficult locations, and the number of practical applications has continued to increase. The basic requirements of shotcrete are adequate adhesion to the substrate, satisfactory shooting stiffness and high early strength preventing dangerous fallout of fresh material from walls and overheads. A new generation of alkali-free accelerators has been used to achieve such properties. However, these chemicals significantly change the microstructure development during setting and hardening of mortar and concrete. UPV appears to be clearly sensitive to the effect of cement type, accelerator type and dosage on the setting behaviour of shotcrete. Apparently, stepwise increase of the accelerator dosage resulted in increasing values for the pulse velocity at early ages (Belie et al., 2005).

UPV may be successfully used to assess the changes in physical or mechanical properties when sustainable concretes are developed. Albano et al. (2005) used tyre tread scrap as a substitute for fine aggregates in concrete. When the weight proportion increased and particle size of the scrap rubber decreased (0.59 and 0.29 mm), flow and density of concretes in the fresh state decreased, as well as compressive strength and splitting tensile strength in the dry state. UPV has proved to be effective to describe the negative impact on mechanical and physical properties, as the percentage of rubber increased (Fig. 17). Mohammed and Abdullahi (2011) have found similar trends with “rubbercrete”.

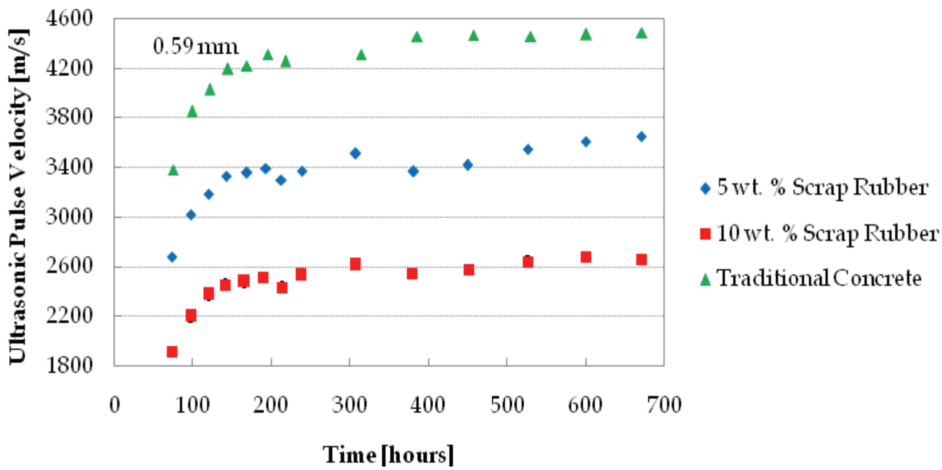


Fig. 17. Variation of ultrasonic pulse velocity with curing time for concrete-rubber mixes without coupling agent (scrap rubber particle size: 0.59 mm)(Albano et al., 2005)

As mentioned in the previous sections, UPV has been used to determine the setting time and hydration of cementitious materials. Keating et al. (1989) has studied oil well cement slurries and some of the important parameters of these cementitious systems. The parameters include the rate of development of static gel strength, the time to initial set, the volume

change and the 'waiting on cement' time for cement to reach a pre-determined strength before drilling operations can continue. These important measurements cannot all be made using a single test technique, and UPV has proved to be one of the satisfactory techniques.
More recently, UPV has been used to correlate physical and mechanical properties in novel cement systems, commonly referred as alkali-activated binders or "geopolymers" (Bondar et al., 2008, Gesoglu, 2010). This technique has the same applicability in geopolymer concretes than in conventional OPC concrete; however, due to its lower density, velocity of pulses in geopolymer concrete tend to be lower than OPC concrete.

5. Summary

Ultrasonic pulse velocity is a valuable technique for characterization of cement-based composites. This chapter shows that this technique has been used for different purposes over the years, e.g. setting and hydration of cement, detection of defects in structures, assessment of damage after high-temperature exposure, incorporation of different aggregates in concrete, among others. It continues to be an important non-destructive technique, which provides reliable results based on rapid measurements with relatively inexpensive equipment.

6. References

Berriman, J., Purnell, P., Hutchins, D.A., Neild, A. (2005). Humidity and aggregate content correction factors for air-coupled ultrasonic evaluation of concrete. *Ultrasonics,* Vol. 43, pp. 211–217.

Bondar, D., Lynsdale, C.J., Milestone, N., Hassani, N., Ramezanianpour, A.A. (2009). Engineering properties of geopolymer concrete based on alkali activated natural pozzolan. *Proceedings of the Third International Conference on Concrete and Development*, Tehran, April 2009.

British Standard BS EN 12504-4 (2004). Testing concrete. Determination of ultrasonic pulse velocity.

Bungey J. H. (1982). *The Testing of Concrete in Structures*. SUNY University Press, New York.

Castro P. F. and Carino N. J. (1998). Tensile and nondestructive testing of FRP bars. *Journal of composites for construction*, February, No. 17.

Cioni, P., Croce, P., Salvatore, W. (2001). Assessing fire damage to r.c. elements. *Fire Safety Journal,* Vol. 36, pp. 181-199.

Chen, W., Shui, Z., Li, W. (2010). Early age hydration of cement paste monitored with ultrasonic velocity and numerical simulation. *Journal of Wuhan University of Technology-Mat. Sci. Ed.*, Vol. 25, No. 4, pp. 704-707.

Chotard, T., Gimet-Breart, N., Smith, A.,Fargeot, D., Bonnet, J.P., Gault, C. (2001). Application of ultrasonic testing to describe the hydration of calcium aluminate cement at the early age. *Cement and Concrete Research,* Vol. 30, pp. 405-412.

Colombo, M., Felicetti, R. (2007). New NDT techniques for the assessment of fire-damaged concrete structures. *Fire Safety Journal,* Vol. 42, pp. 461–472.

Demirboga R., Türkmen I. and Karako M.B. (2004). Relationship between ultrasonic velocity and compressive strength for high-volume mineral-admixtured concrete. *Cement and Concrete Research*, Vol. 34, No. 12, pp. 2329–2336.

Elvery R. H. (1973). Estimating strength of concrete in structures. Current Practice Sheet 10. *Concrete*, Vol. 11, No. 7, pp. 49–51.

Galan A. (1967). Estimate of concrete strength by ultrasonic pulse velocity and damping constant. *ACI J. Proceedings*, Vol. 64, No. 10, pp. 678–684.

Gesoglu, M. (2010). Influence of steam curing on the properties of concretes incorporating metakaolin and silica fume. *Materials and Structures,* Vol. 43, pp. 1123-1134.

Goueygou M., Lafhaj Z., Soltani F. (2009). Assessment of porosity of mortar using ultrasonic Rayleigh waves. *NDT&E International*, Vol. 42, pp. 353–360.

Hola J., Schabowicz K. (2005). Application of artificial neural networks to determine concrete compressive strength based on non-destructive tests. *Journal of Civil Engineering and Management*, Vol. 11, No. 1, pp. 23–32.

Hola J., Schabowicz K. (2005). New technique of nondestructive assessment of concrete strength using artificial intelligence. *NDT&E International*, Vol. 38, No. 4, pp. 251–259.

Ikpong A.A. (1993). The relationship between the strength and non-destructive parameters of rice husk ash concrete. *Cement and Concrete Research*, Vol. 23, pp. 387-398.

Keating J., Hannant D.J., Hibbert A.P. (1989). Correlation between cube strength, ultrasonic pulse velocity and volume change for oil well cement slurries. *Cement and Concrete Research*, Vol. 19, pp. 715-726.

Kewalramani M.A., Gupta R. (2006). Concrete compressive strength prediction using ultrasonic pulse velocity through artificial neural networks. *Automation in Construction*, Vol. 15, No. 13, pp. 374–379.

Kheder G.F. (1999). A two stage procedure for assessment of in situ concrete strength using combined non-destructive testing. *Materials and Structures,* Vol. 32, pp. 410–417.

Kheder, G.F., Al Gabban, A.M., Abid, S.M. (2003). Mathematical model for the prediction of cement compressive strength at the ages of 7 and 28 days within 24 hours. *Materials and Structures,* Vol. 36, pp. 693-701.

Komlos K., Popovics S., Niirnbergeroh T., Babd B. and Popovics J. S. (1996). Ultrasonic Pulse Velocity Test of Concrete Properties as Specified in Various Standards. *Cement and Concrete Composites*, Vol. 18, pp. 357-364.

Krishna Rao, M.V., Rathish Kumar, P., Khan, A.M. (2010). A sudy on the influence of curing on the strength of a standard grade concrete mix. *Facta Universitatis (Series Architecture and Civil Engineering)*, Vol. 8, No. 1, pp. 23-34.

Lafhaj Z., Goueygou M., Djerbi A., Kaczmarek M. (2006). Correlation between porosity, permeability and ultrasonic parameters of mortar with variable water / cement ratio and water content. *Cement and Concrete Research*, Vol. 36, pp. 625 – 633.

Law, D.W., Adam, A.A., Molyneaux, T.K., Patnaikuni, I. (2008). Durability Properties of Geopolymer Mortars. *Proceedings of the 11DBMC International Conference on Durability of Building Materials and Components*, Istanbul, May 2008.

Leslie J. R. and Cheeseman W. J. (1949). An ultrasonic method for studying deterioration and cracking in concrete structures. *American Concrete Institute Proceedings*, Vol. 46, No. 1, pp. 17–36.

Leslie J. R. and Chessman W. J. (1949). An ultrasonic method of studying deterioration and cracking in concrete structures. *Journal of American Concrete Institute*, Vol. 21, No. 1, pp. 17-35.

Lin Y., Lai C.P. and Yen T. (2003). Prediction of Ultrasonic Pulse Velocity in Concrete. *ACI Materials Journal*, Vol. 100, No. 1, pp. 21–28.
Madandoust R., Ghavidel R., Nariman-zadeh N. (2010). Evolutionary design of generalized GMDH-type neural network for prediction of concrete compressive strength using UPV. *Computational Materials Science,* Vol. 49, pp. 556–567.
Mantrala S. K. and Vipulanandan C. (1995). Nondestructive evaluation of polyester polymer concrete. *ACI Material Journal*, Vol. 92, No. 6, pp. 660-668.
Marfisi E., Burgoyne C. J., Amin M. H. G. and Hall L. D. (2005) The use of MRI to observe the structure of concrete. *Magazine of Concrete Research*, Vol. 57, No. 2, pp. 101–109.
Mohammed B.S., Azmi N.J., Abdullahi M. (2011). Evaluation of rubbercrete based on ultrasonic pulse velocity and rebound hammer tests. *Construction and Building Materials*, Vol. 25, pp. 1388–1397.
Nash't I. H., A'bour S. H., Sadoon A. A. (2005). Finding an united relationship between crushing strength of concrete and non-destructive tests, *Proceedings of Middle East Nondestructive Testing Conference & Exhibition*, Bahrain, 2005.
Neville A. M. (1996). *Properties of Concrete*, fourth ed., John Wiley and Sons, Inc., New York.
Nwokoye D.N. (1974). Assessment of the elastic moduli of cement paste and mortar phases in concrete from pulse velocity tests cement and concrete research. Vol. 4, pp. 641-655.
Ohdaira E., Masuzawa N. (2000). Water content and its effect on ultrasound propagation in concrete – the possibility of NDE. *Ultrasonics*, Vol. 38, pp. 546– 552.
Panzera T. H., Rubio J. C., Bowen C. R., Vasconcelos W. L., Strecker K. (2008). Correlation between structure and pulse velocity of cementitious composites. *Advances in Cement Research*, Vol. 20, No. 3, July, pp. 101–108.
Popovics J. S. and Rose L. J. (1994). A survey of developments in ultrasonic NDE of concrete. *IEEE Transactions on Ferroelectrics and Frequency Control*, Vol. 41, No. 1, pp. 140– 143.
Popovics S. (2007). Analysis of the Concrete Strength Versus Ultrasonic Pulse Velocity Relationship, In: *American Society for Nondestructive Testing*, 12th of December 2010, Available from: <http://www.asnt.org/publications/materialseval/basics/feb01basics/feb01basics. htm>.
Prassianakis I. N. and Giokas P. (2003). Mechanical properties of old concrete using destructive and ultrasonic non-destructive testing methods. *Magazine of Concrete Research*, Vol. 55, No. 2, pp. 171–176.
Pundit. (1993). Manual of Portable ultrasonic non destructive digital indicating tester, C. N. S. Instruments, London.
Qasrawi Y.H. (2000). Concrete strength by combined non-destructive methods simply and reliably predicted. *Cement and Concrete Research*, Vol. 30, No. 6, pp. 739–746.
Rajagopalan P.R., Prakash J. and Naramimhan V. (1973). Correlation between ultrasonic pulse velocity and strength of concrete. *Indian Concrete. Journal*, Vol. 47, No. 11, pp. 416–418.
Reinhardt, H.W., Grosse, C.U. (2004). Continuous monitoring of setting and hardening of mortar and concrete. *Construction and Building Materials*, Vol. 18, pp. 145–154.
Reinhardt, H.W., Große, C.U., Herb, A.T. (2000). Ultrasonic monitoring of setting and hardening of cement mortar – a new device. *Materials and Structures*, Vol. 33, pp. 580-583.

Rio L.M., Jimenez A., Lopez F., Rosa F.J., Rufo M.M., Paniagua J.M. (2004). Characterization and hardening of concrete with ultrasonic testing. *Ultrasonics*, Vol. 42, pp. 527–530.

Shkolnik I.E., Udegbunam O.C., Aktan H.M. (1997). Ultrasonic methods of evaluating concrete permeability. *Proceedings of the Conference on NDT in Civil Engineering, British Institute of NDT*, University of Liverpool, pp. 111 –120.

Tanyidizi, H. Coskun, A. (2008). Determination of the principal parameter of ultrasonic pulse velocity and compressive strength of lightweight concrete by using variance method. *Russian Journal of Nondestructive Testing,* Vol. 44, No. 9, pp. 639–646.

Tharmaratram K. and Tan B.S. (1990) Attenuation of ultrasonic pulse in cement mortar. *Cement and Concrete Research,* Vol. 20, pp. 335–340.

Trtnik G., Kavcic F., Turk G., (2009). Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks *Ultrasonics* Vol. 49, pp. 53–60.

Trtnik G., Turk G., Kavèiè F., Bosiljkov V. B. (2008). Possibilities of using the ultrasonic wave transmission method to estimate initial setting time of cement paste. *Cement and Concrete Research*, Vol. 38, pp. 1336–1342.

Turgut P. (2004). Evaluation of the ultrasonic pulse velocity data, *Proceedings of Fourth International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components*, London, 2004.

Turgut P., Kucuk O. F. (2006). Comparative relationships of direct, indirect, and semi-direct ultrasonic pulse velocity measurements in concrete. *Russian Journal of Nondestructive Testing*, Vol. 42, No. 11, pp. 745–751.

Udegbunam O., Yaman I., Aktan H., Hohm T. (1999). Developing a rapid measure of concrete permeability for use in QA/QC specifications. Proceedings of Transportation Research Board, 78th Annual Meeting, January 10– 14, Washington D.C., 1999.

Ulucan Z. Ç., Türk K. and Karata M. (2008). Effect of mineral admixtures on the correlation between ultrasonic velocity and compressive strength for self-compacting concrete. *Russian Journal of Nondestructive Testing,* Vol. 44, No. 5, pp. 367–374.

Vergara L., Miralles R., Gosalbez J., Juanes F.J., Ullate L.G., Anaya J.J., Hernandez M.G., Izquierdo M.A.G. (2001). NDE ultrasonic methods to characterise the porosity of mortar. *NDT & E International*, Vol. 34, pp. 557–562.

Vipulanandan C. and Garas V. (2008) Electrical resistivity, pulse velocity and compressive properties of carbon fiber reinforced cement mortar. *Journal of material in Civil Engineering*, pp. 93-101.

Winkler K., Nur A. (1982). Seismic attenuation: effects of pore fluids and frictional sliding. *Geophysics*, Vol. 47, No. 1, pp. 1 – 15.

Yaman I.O., Hearn N., Aktan H.M., (2002). Active and non-active porosity in concrete: Part I. Experimental evidence. *Materials and Structures*, Vol. 35, No. 246, pp. 102– 109.

Yaman I.O., Aktan H.M., Hearn N. (2002). Active and non-active porosity in concrete: Part II. Evaluation of existing models. *Materials and Structures*, Vol. 35, No. 246, pp. 110–116.

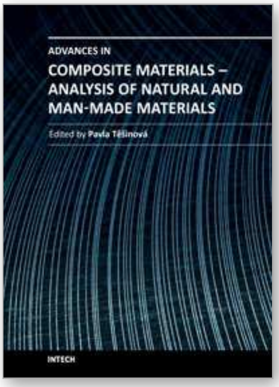
Yazicioglu, S., Caliskan, S., Turk, K. (2006). Effect of curing conditions on the engineering properties of self-compacting concrete. *Indian Journal of Engineering & Materials Science,* Vol. 13, pp. 25-29.

Ye, G., van Breugel, K., Fraaij, A.L.A. (2001). Experimental study on ultrasonic pulse velocity evaluation of the microstructure of cementitious material at early age. *Heron,* Vol. 46, No. 3, pp. 161-167.

Yildirim H., Sengul O. (2011). Modulus of elasticity of substandard and normal concretes. *Construction and Building Materials*, Vol. 25, pp. 1645–1652.

Zhang, J., Qin, L., Li, Z. (2009). Hydration monitoring of cement-based materials with resistivity and ultrasonic methods. *Materials and Structures,* Vol. 42, pp. 15-24.

Zarandi M.H. F., Turksen I.B., Sobhani J., Ramezanianpour A.A. (2008). Fuzzy polynomial neural networks for approximation of the compressive strength of concrete. *Applied Soft Computing*, Vol. 8, No. 1, pp. 488–498.



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Composites are made up of constituent materials with high engineering potential. This potential is wide as wide is the variation of materials and structure constructions when new updates are invented every day. Technological advances in composite field are included in the equipment surrounding us daily; our lives are becoming safer, hand in hand with economical and ecological advantages. This book collects original studies concerning composite materials, their properties and testing from various points of view. Chapters are divided into groups according to their main aim. Material properties are described in innovative way either for standard components as glass, epoxy, carbon, etc. or biomaterials and natural sources materials as ramie, bone, wood, etc. Manufacturing processes are represented by moulding methods; lamination process includes monitoring during process. Innovative testing procedures are described in electrochemistry, pulse velocity, fracture toughness in macro-micro mechanical behaviour and more.

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