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APPLICATION OF ULTRASONIC METHODS FOR EARLY AGE CONCRETE CHARACTERISATION

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ABSTRACT

Concrete setting and hardening process are the most critical phases during construction works, influencing to properties of concrete structure, so the application of efficiency non-destructive test methods for early age concrete properties determination is crucial. Penetrometer, pull out and Vicat needle methods are standardized methods for young concrete characterisation. Paper shows that ultrasound methods have potential to be used for these purposes. Ultrasonic waves can propagate through media as transversal, longitudinal and Rayleigh waves. Material properties can be determined based at phase, velocity, frequency, attenuation, relaxation and reflection measurements. With ultrasonic methods, it is possible to determine the kinetics and degree of hydratation, setting time, compressive strength and dynamic modulus of elasticity. Measurements of longitudinal compressive wave velocity through concrete and mortar during hardening process are performed. For mixtures preparation different additives were used. Obtained results indicate possibility for hardening process monitoring and time of cementitous materials setting determination.

***Keywords**:* Ultrasonic testing, Early age concrete, Acoustic waves, Nondestructive testing

1. Introduction

Setting and hardening of fresh concrete are the most critical phases during the construction works, on which depend properties of concrete structure during its service life. During setting process concrete mixture transforms from fluid state which properties is important for placing into formworks into solid whose properties are important for the proper behaviour of material in the service. Control of hardening phenomena can be used for determination of right moment for formwork removal, or load the structure. So, knowledge of fresh and young concrete is important from both, technical and economical aspects. It follows that accurate and useful testing methods for properties of young concrete properties determination are of great interest. Conventional testing methods for fresh concrete and mortar properties determination are slump cone test, flow table test, penetration needle test, Vicat apparatus test, hydratation temperature measurement, and for young concrete pull-out test. Main drawback of these methods is missing of continuous measurement data. Rhelological testing methods which use different types of viscosimeters

mainly isn't successful because apparatus acts to fresh concrete with shear forces which destroy microstructure in the early ages of hydratation process.
Between alternative approaches ultrasound testing methods seems to be successful for more accurate determination of these properties.

2. Properties of cementitous paste

Cementitous paste from preparation to finish of hardening process rashly changes microstructure which acts to its viscosity, elasticity and plasticity. From Newtonian fluid state in the time of preparation, it transforms into Bingham and Kelvin body.
Newtonian fluid has linear dependence between pressure and flow rate. Bingham body is soft and very plastic material with property that with influence of small shear stress first has elastic deformation. With the exceeding of yield stress which corresponds to elasticity limit it obtains Newtonian fluid properties. Kelvin body is also elastic, but returns into original shape with the time delay. For larger shear stresses plastic deformation is added to elastic deformation and cementitous paste loss properties of Kelvin rigid body.
In the first few hours after preparation microstructure of fresh concrete is very brittle. In contrast to conventional testing methods, ultrasound waves with enough small energy can't disturb microstructure.

3. Theory of acoustic wave propagation through viscoelastic media (Voight model)

Voight model describes properties of viscolastic materials, which are characterised with time dependent relation between stress and strain. In the phase of setting viscous properties concrete are dominant and elastic properties increases with time.
Hardened concrete is viscoelastic material, but if stresses isn't too big and in the enough short period of time it shows elastic properties according to Hooke's law.
Starting point of Voight model is differential equation (1), where the first term describes behaviour of ideally elastic material with deformation proportional to stress, and second term describes viscous material where deformation is time dependent for applied stress.

$$\sigma = Y\varepsilon + \eta \frac{\partial \varepsilon}{\partial t} \tag{1}$$

Where: η - Viscosity of medium
ε - Deformation
Y - Young modulus of elasticity

With application of constant stress $\sigma=\sigma_0$ on system, solution of differential equation (1) is:

$$\varepsilon = \frac{\sigma_0}{Y} \cdot \left(e^{\frac{-t}{\tau}} \right) \tag{2}$$

$$\tau = \frac{\eta}{Y} \tag{3}$$

Where: t – Time from starting of stress application
τ - Time constant dependent on material properties

System transforms from the state without stress into the state with stress σ_0 by a relaxation process with time constant τ, which depend on Young modulus of elasticity and on viscosity.
For phase wave velocity through viscoelastic media can be obtained:

$$v_p = \sqrt{\frac{Y}{\rho}} \tag{4}$$

Waves in material shows property of attenuation which is function of angular frequency (ω), density of material (ρ), viscosity (η) and on phase velocity (v_p), according to relation:

$$\alpha = \frac{\omega^2 \tau}{2v_p} = \frac{\omega^2 \eta}{2\rho v_p{}^3} \tag{5}$$

From these theoretical considerations follow possibility, that properties of fresh concrete can be determined from system relaxation time measurement after ultrasonic impulse application, by measuring of phase velocity of elastic waves, or by measurement of signal attenuation along the tested specimen.

4. Theory of acoustic wave propagation through elastic media

Mechanical provoked surface disturbance on rigid body propagate through material in the form of acoustic waves which can be described with wave equation:

$$\frac{\partial^2 \vec{u}}{\partial t^2} = v^2 \Delta^2 \vec{u} \tag{6}$$

Where: $\vec{u}(x,y,z,t)$ - displacement vector
v - velocity of acoustic waves

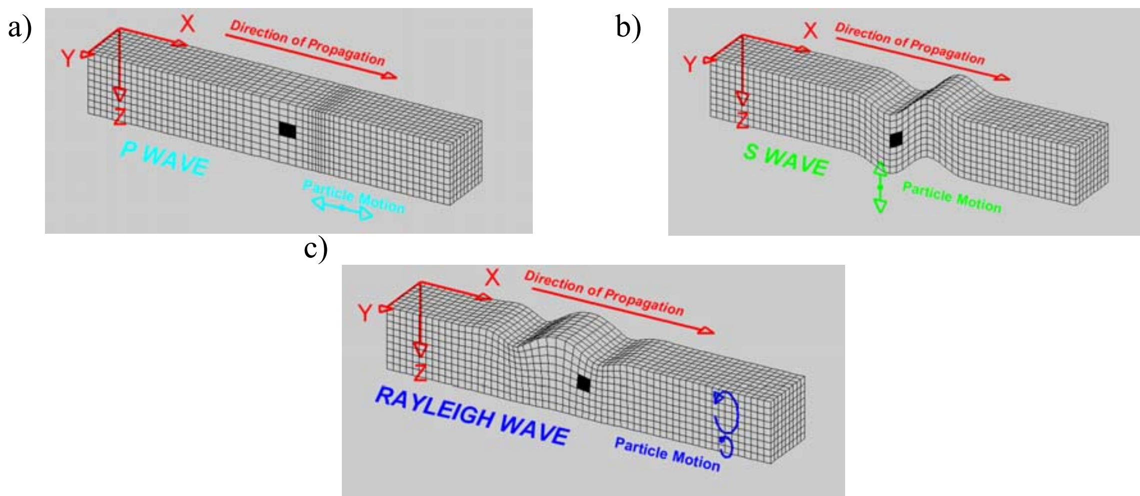

Fig. 1: Propagation of a) Longitudinal (P) waves, b) Transversal (S) waves and c) Rayleigh waves through material.

Through rigid material longitudinal (P), transversal (S) and Rayleigh (R) acoustic waves can be propagated. Longitudinal waves have direction of particle movement parallel with the direction

of wave front spreading, but for transversal waves these directions are normal. Rayleigh waves propagate on the surface of material and their amplitude has fast exponential decrease with depth of material. Figure 1 shows different modes of wave propagation.
Many non-destructive testing methods based on ultrasonic, use properties of all three types of waves [1].
Longitudinal and transversal wave velocity is related with elastic properties of material by relations (7) and (8), respectively.

$$v_L = \sqrt{\frac{E(1-\upsilon)}{(1+\upsilon)(1-2\upsilon)\rho}} \tag{7}$$

$$v_T = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2(1+\upsilon)\rho}} \tag{8}$$

Where: v_L - Velocity of longitudinal waves
v_T - Velocity of transversal waves
E - Dynamical Young modulus of elasticity
G - Shear modulus of elasticity
ρ - Density of material
ν - Poisson coefficient

It is obvious from relations (7) and (8) that for testing methods which use velocity measurement of transversal and longitudinal waves, for evaluation of Young modulus of elasticity, Poisson coefficient determination is necessary.
By combination of both relations, modulus of elasticity and Poisson coefficient can be expressed as a function of longitudinal wave and transversal wave velocities (v_L and v_T) according to relations (9) and (10).

$$\upsilon = \frac{1-2\left(\frac{v_L}{v_T}\right)^2}{2-2\left(\frac{v_L}{v_T}\right)^2} \tag{9}$$

$$E = 2\rho v_T^{\,2}(1+\upsilon) \tag{10}$$

Therefore, with simultaneous measurement of longitudinal and transversal waves velocity, modulus of elasticity and Poisson coefficient can be determined.
Third type of waves is Rayleigh waves, which is characterised with spreading in the field near the surface of material. Amplitude of Rayleigh waves rashly exponentially decreases with depth. Rayleigh wave propagation velocity can be determined from the Bergman approximation:

$$v_R = \frac{0{,}87+1{,}12\upsilon}{1+\upsilon} v_T \tag{11}$$

5. Measurements based on velocity of longitudinal waves

Ultrasound test method with short pulses of longitudinal waves is used to study setting and hardening processes on two concrete mixtures: without admixture and with addition of retarder

(Table 1). To perform measurements, 10×10×30 cm concrete prisms were prepared. Simultaneously with the measurements of ultrasound velocity, setting time was determined by means of penetrometer on separate specimens (Fig. 2).

Table 1: Mixture composition.

	Mixture I	Mixture II
Cement (kg)	450 kg	450 kg
w/c	0.45	0.45
Admixture (retarder)	-	6.75 kg
D_{max} (mm)	8	8

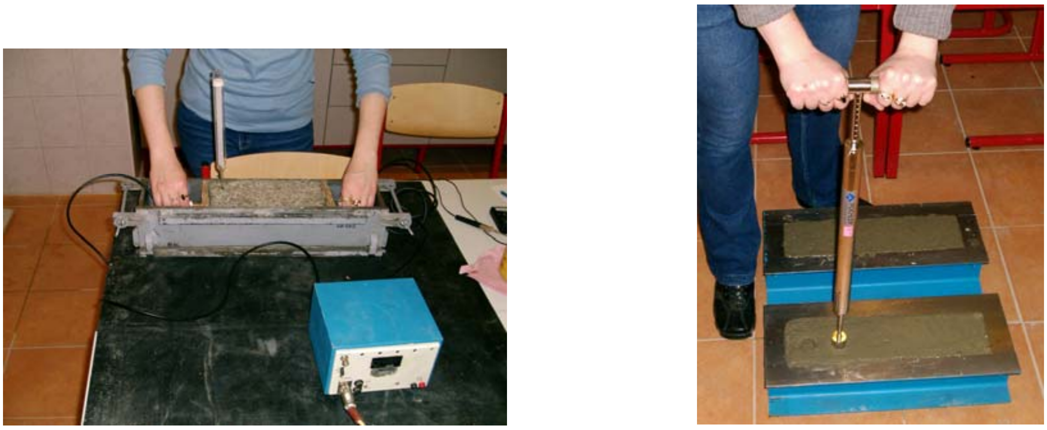

Fig. 2: Ultrasound measurements and setting time determination by means of penetrometer.

a)

b)

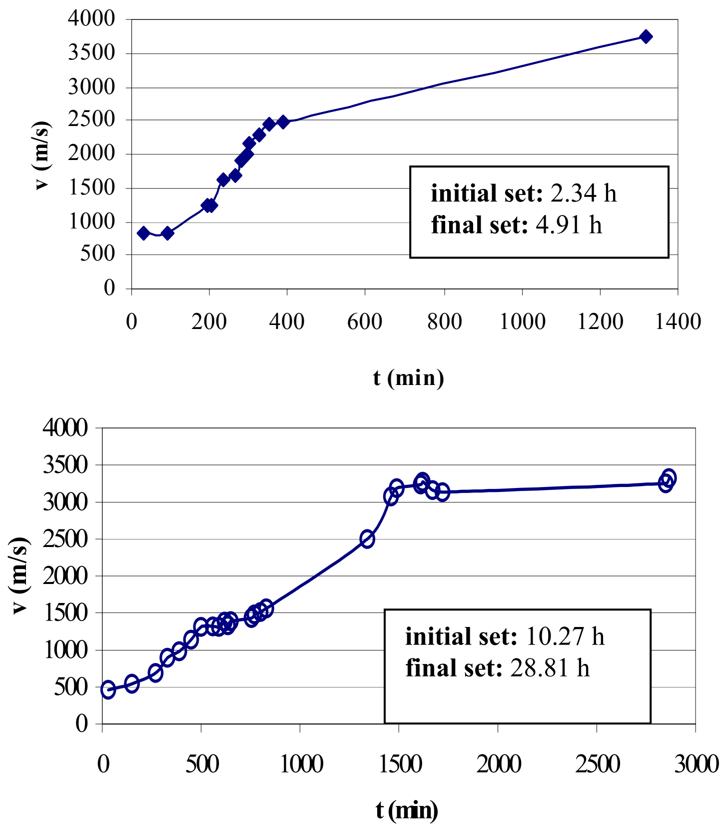

Fig. 3: Velocity in time for a) concrete without admixture (mixture I) and b) concrete with addition of retarder (mixture II).

Test results for the two concrete mixtures are shown in Figure 3. First two hours after mixing fresh concrete contains many air bubbles which results with small and constant velocity of ultrasonic waves, for some extent greater than ultrasonic velocity in air. As content of air decreases, velocity increases to about 1500 m/s which corresponds to ultrasonic wave velocity in water, as shown in figure 3. With the hydratation process development, concrete lose water and ultrasonic wave velocity increase slower of, which is shown at the right side of graphs in Figure 3.
Impulse velocity to a great extent depends on the hydration process in cement paste. Impulse spreads faster through void filled with water than through air void. Consequently, moisture content directly affects on impulse velocity. To a certain degree, that is the weak point of ultrasound testing of concrete setting time. However, it is shown that during the process of hardening velocity increase.
Obtained results are in agreement with results of other authors. Herb, Reinhardt and Grosse conducted measurement of longitudinal acoustic wave velocity, using concrete mixtures with different admixtures and different water to cement ratio [2, 3]. Results represented in figure 4 shows that wave velocity increases with age, dependent on used admixture and on w/c ratio.

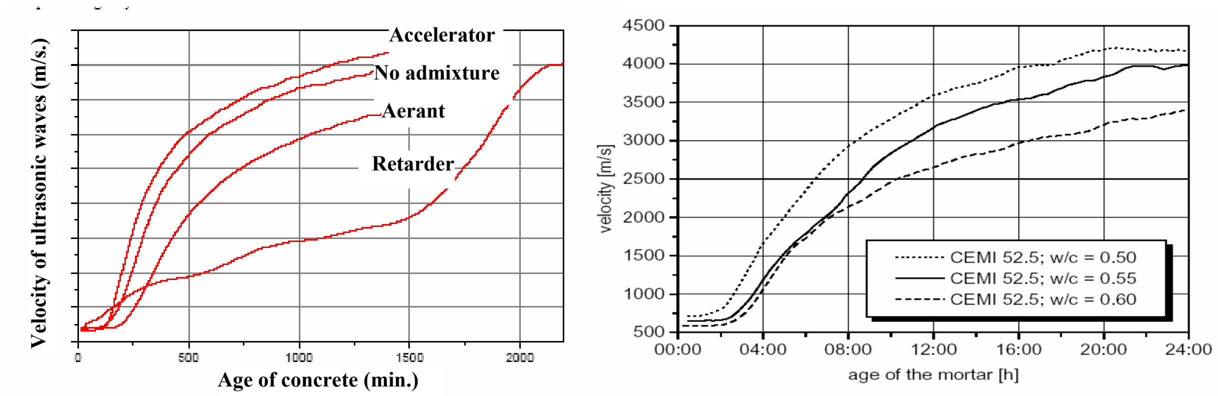

Fig. 4: velocity of P waves dependent on setting and hardening process for a) different admixtures [2] and b) different w/c ratios [3].

Frequency dependent analysis of signal intensity provides transmission of energy through the material calculation. Transmission of energy increases as modulus of elasticity decrease, and decrease as viscosity increase. Figure 5 shows transmitted energy and elastic wave velocity during cementitous mortar setting with addition of retarder [4].

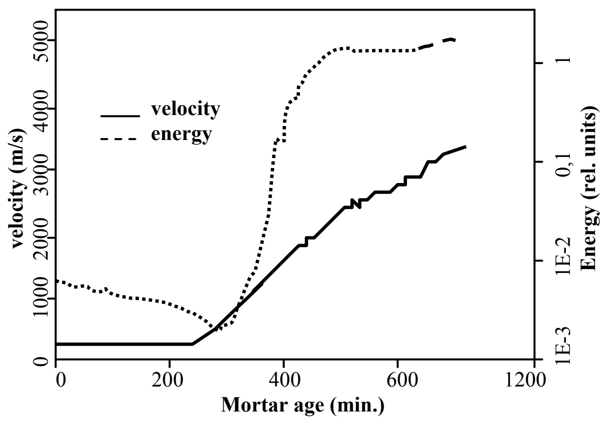

Fig. 5: Transmitted energy and velocity of P waves during cementitous mortar setting [4].

6. Measurements based on velocity of transversal waves

It is well known that transversal ultrasonic waves can propagate in the rigid bodies, but not in the fluids. This makes possible determination of initial setting time for concrete or mortar mixtures. Initial setting time is characterised with growth of large prismatic crystals of calcium hydroxide and very small fibrous crystals of calcium silicate hydrates, which begin to fill the empty space formerly occupied by water and the dissolving cement particles. In the point of initial setting, concrete suddenly start to conduct transversal ultrasonic wave, so this moment can be determined with great accuracy [7].

7. Reflection of elastic waves measurement

Method of elastic waves reflection use measurement of the reflection coefficient between steel plate inserted into concrete and concrete. For experiments, beside steel successfully was used quartz or polymethyl methacrylate [5,6]. Figure 6 shows experimental device [8].

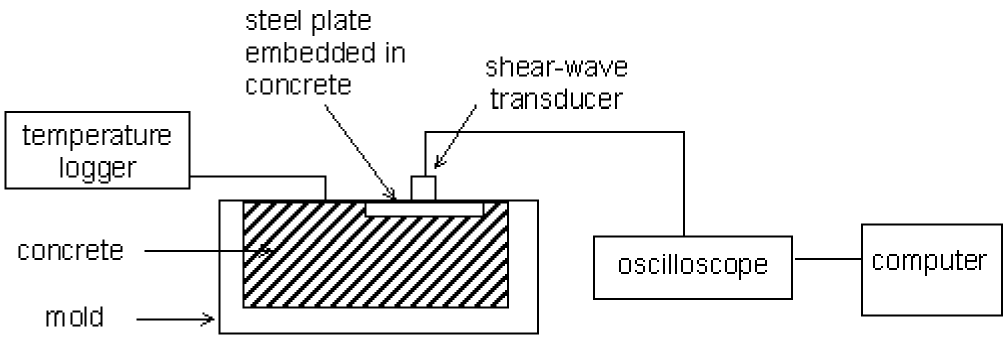

Fig. 6: Schematic representation of device for determination of young concrete properties by the reflection loss method.

Piezoelectric transducer transmits ultrasonic wave pulse into steel and transmission of acoustic waves into concrete changes dependent on phase of concrete setting.
Measured results are represented with the reflection coefficient expressed in decibels which is in the literature [8, 9] usually named as a reflection loss ($R_L(t)$) or wave reflection factor (WRF). Reflection loss describes relation (12), where $A_{r1}(t)$ and $A_{r2}(t)$ are amplitudes of first and second signal reflected on the boundary between steel plate and concrete.

$$R_L(t) = -20 \log \frac{A_{r2}(t)}{A_{r1}(t)} \tag{12}$$

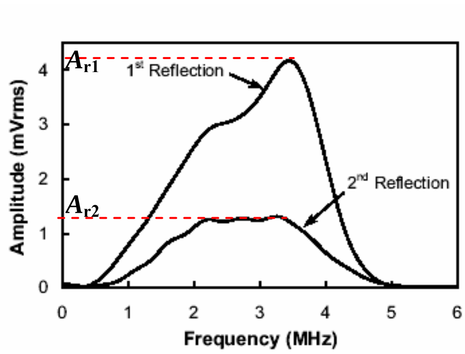

Fig. 7: First and second reflection of measured signal.

Figure 7 shows first and second reflection of measured signal expressed in the frequency domain [10].
Figure 8 illustrate experimental results of reflection loss measurements which is dependent to concrete setting and hardening. Simultaneously, hydratation temperature was measured. Until starting of the hydratation reaction $R_L(t)$ have value of 1 approximately. With the cement hydratation temperature increases, reflection loss decreases, and after end of exothermic reaction (induction period), decrease of $R_L(t)$ is slower and linear. It seems that reflection loss method can be used for initial and final setting time determination which is marked in the Figure 8 with numbers 1 and 2. Reflection loss method can be used instead of conventional penetration measuring methods.

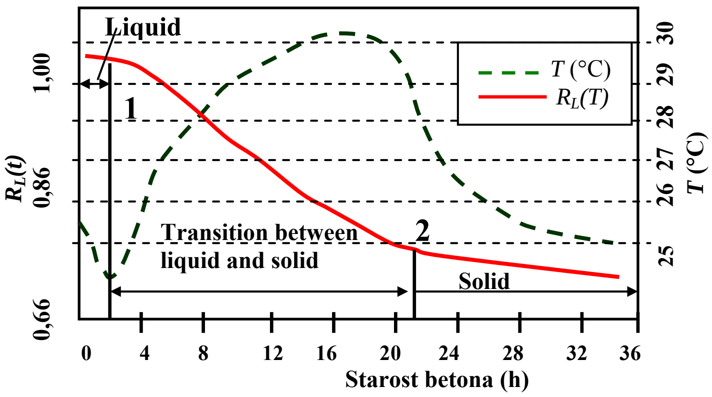

Fig. 8: Reflection loss and temperature of concrete during the hydratation process development [8].

From a part of curve after point 2 (Fig. 8), where concrete is hardened, it is possible to follow development of mechanical properties as a modulus of elasticity and strength.
Experimental results [9] have linear dependence of R_L(t) to compressive strength, as shown in Figure 9.

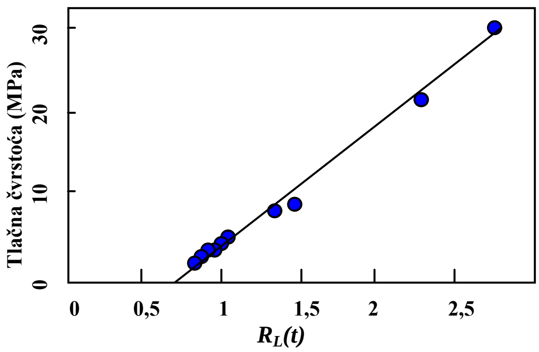

Fig 9: Reflection loss as a function of concrete compressive strength [9].

Figure 10 illustrates experimental results which show decrease of a WRF with concrete setting and hardening process for different used admixtures [10].
By comparing pastes of different water-cement ratio (Fig. 11.), it can be seen that the slope of the linear regression lines changes with water-cement ratio [11]. The paste with the lowest water-cement ratio has the biggest slope, while a higher water-cement ratio corresponds to a lower slope. This difference is due with the different microstructure in the cement pastes. For the same degree of hydration, cement paste with w/c=0.35 has much more solid phase than the paste with

higher water-cement ratio. Since solid phase make possible wave propagation, larger amount of solid phase in microstructure corresponds to higher reflection loss.

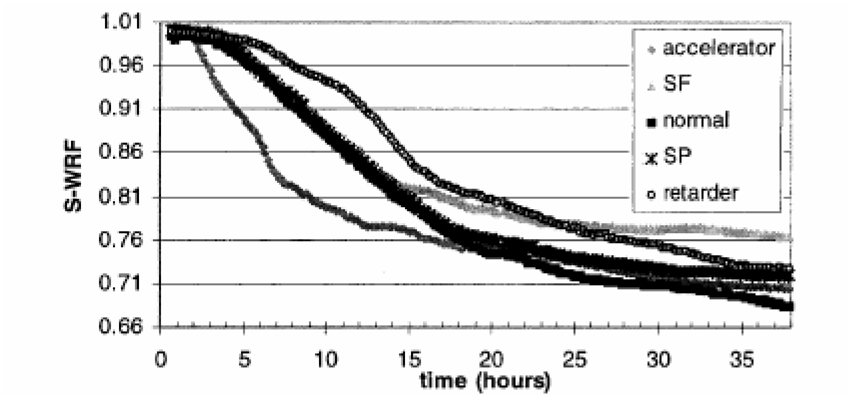

Fig. 10: Decrease of a WRF factor with time [10].

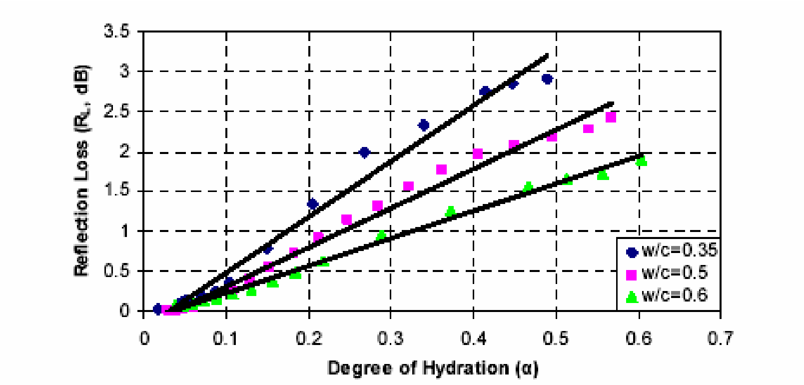

Fig. 11: Reflection loss as a function of degree of hydratation for different w/c ratio samples [11].

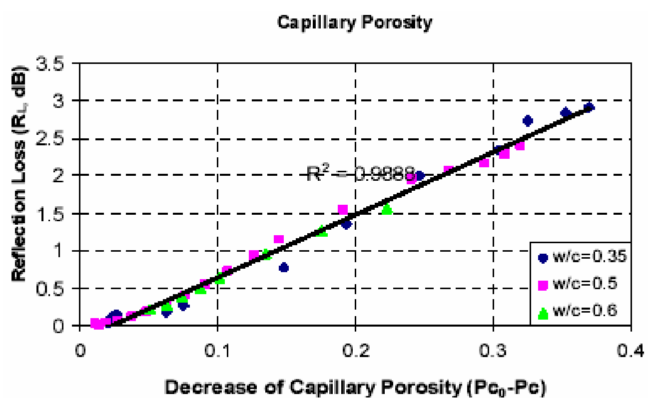

Fig. 12: Correlation between the reflection loss and decrease of capillary porosity [11].

Figure 12 shows linear correlation between a reflection loss and decrease of capillary porosity. Decrease of capillary porosity is defined as a difference between the volume fraction of pore phase at initial stage (P_{c0}) and the capillary porosity (P_c) for a given degree of hydration. Changing rate of reflection loss with respect to decrease of capillary porosity is independent to water-cement ratio.

8. Conclusions

Ultrasonic testing methods can be based on the measurement of relaxation, attenuation, velocity and reflection of longitudinal, transversal or Rayleigh ultrasonic waves [12].
Paper describes only some of these approaches to the measurement of setting and hardening of concrete. Results of P-waves velocity measurement is in a good agreement with results obtained by the other authors. Our results indicate that moisture and air content directly affects on impulse velocity, which is to a certain degree the weak point of ultrasound testing of concrete setting time. For successful application of ultrasonic methods knowledge about time development of material properties during hydratation process and physical properties of ultrasonic waves is crucial.

9. References

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