MONITORING of CONCRETE HARDENING USING ACOUSTO-ULTRASONIC METHOD

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***ABSTRACT** - In civil engineering practice there is often the need for estimation of compressive strength of concrete during construction process and for that purpose different testing methods have been proposed. This paper deals with application of acousto-ultrasonic (AU) measurement method for monitoring of strength development process in concrete and presents outcomes of an experimental investigation on six concrete mixtures prepared with two types of cement and three different w/c ratios. Experimental work was conducted in Laboratory for materials testing at Civil Engineering Faculty in Zagreb.*

***Keywords:** compressive strength, acousto-ultrasonic, early age concrete*

1. INTRODUCTION

Estimation of compressive strength of concrete at a certain age after casting usually serves as a toll for speeding up of construction or production process because it enables determination of time when the structure is ready to carry loads so that removal of formwork or pre-stressing can be done without the risk collapse, cracking or large deformations. Development of strength of concrete is a result of cement hydration process which is most intensive during the first few days after mixing. During that period increase in quantity of hydration products formed is largest and increase of strength and rigidity of concrete are fastest. Because progress of hydration reflects as changes of chemical, physical, mechanical and electrical properties of concrete it can be monitored by measuring changes in chemical composition, enthalpy, ultrasonic wave velocity, volume, consistency or strength.

Ultrasonic methods have been used for monitoring of concrete properties since middle of 20th century. Ultrasonic waves or more generally stress waves propagate through solids and interact with material.

According to Nagy the primary purpose of ultrasonic non-destructive evaluation is to understand the wave-material interaction and assess the sought material properties from the observed deviation in the ultrasonic response from that of an ideal, defect-free medium [1]. This definition is valid for solid materials whose properties remain constant during testing. In ultrasonic testing of early-age concrete there is no ideal - defect free medium but instead deviations caused by changes in the material properties are studied.

Probably mostly used method for monitoring of strength development in concrete is ultrasonic pulse velocity (UPV). Although vide variety of strength-velocity correlations can be found in the literature Popovic states that parameters like composition of concrete, temperature, curing, and so on do not have the same effect on the concrete compressive strength development and on the ultrasonic wave velocity and this precludes setting up of a reliable regression model for estimation of compressive strength [2]. On the other hand shear wave reflection method was proven to have almost linear correlation with strength development of concrete [3, 4]. Another great advantage of this method is that it can be applied in-situ and only one side of element has to be available for testing.

In the research presented in this paper an acousto-ultrasonic (AU) method was used for monitoring of changes in early-age concrete. AU method is closely related to the acoustic emission. While acoustic emission requires loading in AU stress waves are generated externally, usually by a transducer [5]. Philippidis and Aggelis had already shown that AU is sensitive to the structural changes in concrete [6]. One of the main differences between ultrasonic and AU testing is in sensors used to collect signals. While in ultrasonics longitudinal or shear wave sensors are used acoustic emission sensors are sensitive to both longitudinal and transversal motion of the surface.

2. METHODS

AU measurement system is assembled which had the ability to continuously record waveform information. Measurements are made on concrete of different mix compositions during the first few days of hydration in Laboratory for materials testing at Civil Engineering Faculty in Zagreb. Results obtained are compared to the properties of concrete tested using complementary testing methods which included compressive strength test and UPV monitoring.

2.1. The AU setup

Scheme of AU setup is presented in Figure 1. Sensors are placed on the opposite sides of a specimen at the center of the surface. Waveform generator produces a pulse of 10 V which excites one piezoelectric sensor. The stress wave propagates through the material and it excites another sensor of the same type, which is attached on the opposite surface. This signal is then preamplified, digitized and stored as a waveform. The equipment used consists of two piezoelectric transducers R6 of Physical Acoustics Corporation (PAC), resonant nominally in the range 20–120 kHz, arbitrary waveform generator ARB-1410-150, PAC 1220 preamplifiers with selectable gain of 0/20/40 dB and a PAC 16 bit PCI-8 data acquisition system. Waveforms were recorded at a sampling rate of 1 MHz, which is considered adequate considering the frequency range of R6 sensors. The same sensors were used as pulser and receiver through the entire experimental work presented in order to avoid influence of different sensor characteristic on measurement results. During measurement pulse repetition frequency on 0,01 Hz was used which is equal to one pulse every 100 seconds. AU measurements were started when concrete was still in the fresh state.

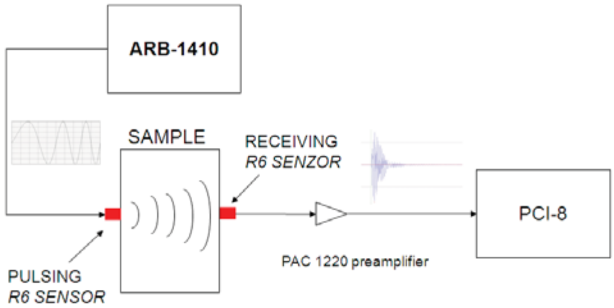

Figure 1 *Scheme of AU testing setup*

In order to achieve that adequate mold had to be made. Mold consisted of extruded polystyrene 2 cm thick and water resistant plywood frame connected with bolts. Dimension of the concrete specimens in the mold are 15x15x10cm. Distance between sending and receiving sensor was 10 cm for testing concrete and 7 cm for testing of cement paste (in this paper only results of testing concrete are presented). After mixing concrete was cast into mold and compacted by a handheld vibrator because it was noted that compaction on vibrating table didn't gave satisfactory compaction probably due to the damping of vibrations caused by XPS. Before placing of concrete into mold PE-LD foil was placed in mold between concrete and XPS. This was made in order to prevent evaporation of water from concrete and shrinkage which can cause reduction of stress wave energy transmission between sensors and specimen. A layer of water was also placed on top of each specimen during AU measurement. After compaction specimens were placed in a temperature controlled room with temperature 19 ± 2°C. Sensors were then mounted and slightly pressed against specimen through

PE-LD foil. A layer of grease is applied in the sensor-foil interface to assure acoustical coupling. Contact of specimen and sensors was maintained using sensor holders (Fig. 2).

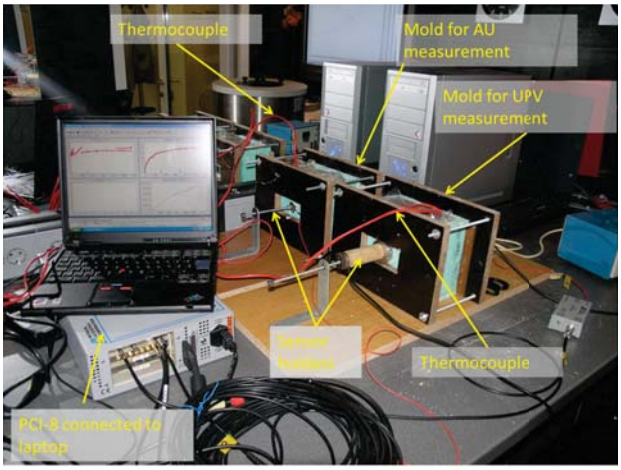

Figure 2 *Experimental setup during testing*

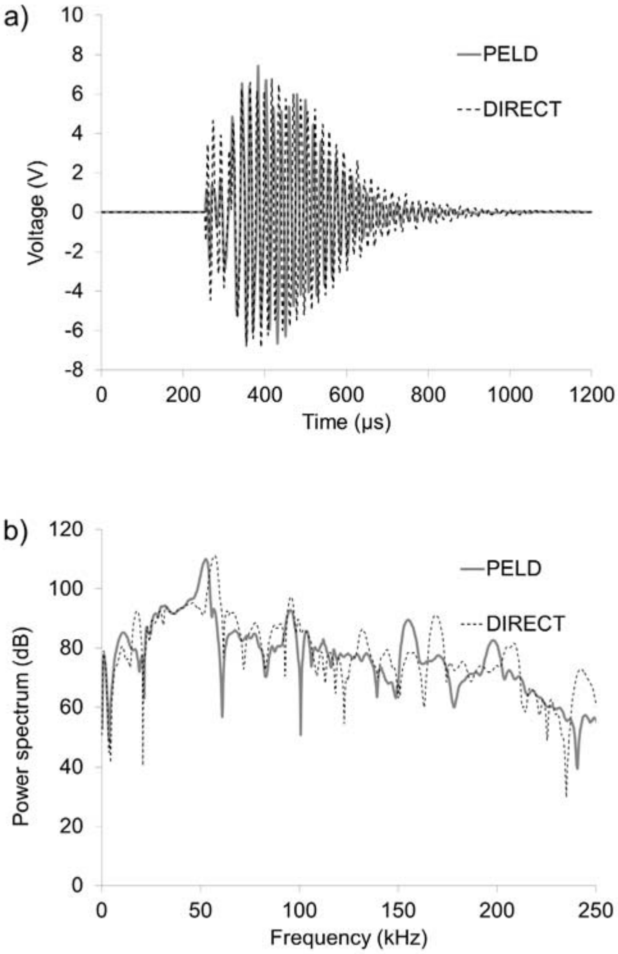

Figure 3 *Comparison of waveforms obtained in a face to face configuration with sensors in direct contact and through PELD: a) time domain and b) frequency content*

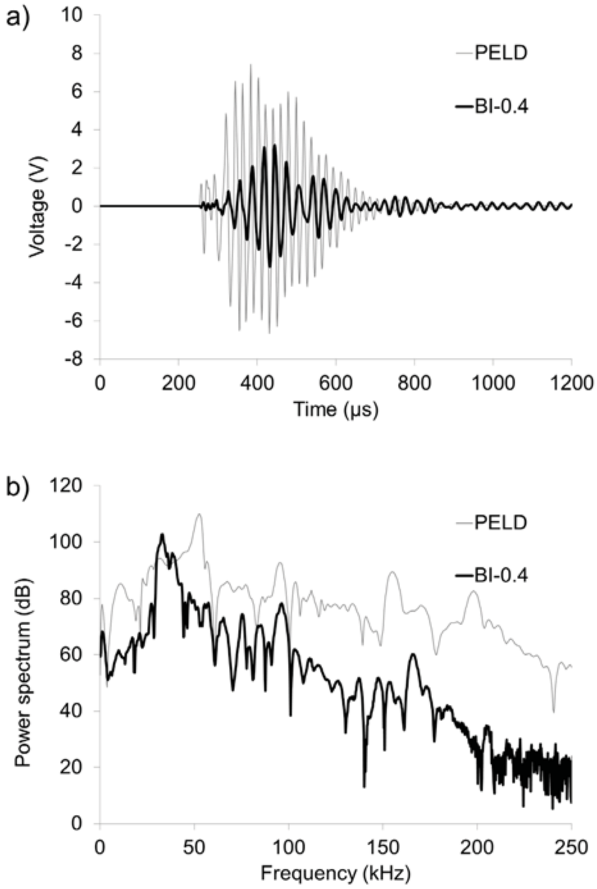

Figure 4 *Comparison of waveforms – through PELD in a face-to-face configuration and waveform recorded during test for mixture BI-0.4 at an age of concrete 48 hours: a) time domain and b) frequency content*

In figure 3 waveforms obtained in a face-to-face configuration in direct contact and through two layers of PELD foil are compared in order to estimate influence of PELD foil on the waveform characteristics. Three replicate measurements were made on each case of configuration and each time 100 waveforms was recorded. The energy content of the signal is evaluated through the parameter signal strength. Signal strength is calculated as the area under the rectified waveform. By placing 2 layers of PELD between sensors energy transfer is reduced by 9 % while peak frequency is shifted from 57 kHz to 54 kHz. In figure 4 comparison of the signal obtained in a face-to-face configuration through PELD to the signal transferred through 10 cm sample of concrete form mix BI-0.4 recorded at the age of concrete of 48 hours. From figure 4a) it can be seen that the amplitude of the waveform is reduced when passing through concrete which is influenced by increased travel length but also by different transmission-reflection conditions at the interfaces. From figure 4b) is can be seen that frequency peak is shifted toward lower frequency when passing through the concrete.

2.2. Concrete mix design

Two types of cement were used for making concrete specimens: ordinary Portland cement CEM I 42,5 R (OPC) and blast furnace slag cement CEM III/B 32,5 N SR-LH (CEM III) in which 66-80% of Portland cement clinker is replaced by a ground granulates blast furnace slag. Slag cement is used during experimental work because slag has a large impact on the kinetics of hydration. Six concrete mix compositions were used during experimental work. Besides cement type w/c ratio was varied in the range form 0,4-0,65. Aggregate used was dolomite. Three fractions were used for making concrete: 0-4 mm (35,6 %), 4-8 mm (24,0 %) and 8-16 mm (40,4 %). Concrete mix proportions are presented in Table 1. Mixtures are labelled according to cement type and w/c ratio of the mix.

Table 1 *Concrete mix composition*

Cement	*OPC*			*CEM III*		
Mixture	*BI-0.4*	*BI-0.5*	*BI-0.65*	*BIII-0.4*	*BIII-0.5*	*BIII-0.65*
w/c	*0,4*	*0,5*	*0,65*	*0,4*	*0,5*	*0,65*
Water, kg	*190*	*190*	*190*	*190*	*190*	*190*
Cement, kg	*475*	*380*	*292*	*475*	*380*	*292*
Aggregate, kg	*1793*	*1879*	*1958*	*1764*	*1856*	*1940*

2.3. Mixing, curing and testing procedures

Approximately 24 hour prior to mixing all concrete components are stored at a temperature 20±2°C. Parallel to AU measurements ultrasonic pulse velocity (UPV) was also measured using the same type of mold like in AU measurements (Figure 2). UPV was measured using Pundit instrument from CNS Farnell with 54 kHz L-wave transducers. UPV was recorded every 60 seconds during measurement. In the specimen under test type K thermocouple was embedded and temperature was recorded at an interval of 5 minutes.

Strength development was evaluated through compressive strength test. After mixing cubes for compressive strength test were compacted on a vibrating table and cured first 24 hours in the molds covered with plastic sheet and then in the curing chamber afterwards at 20±2°C. Concrete strength was tested on standard cubes with 15 cm edge at six different ages after mixing. At each age 3 cubes were tested and the result presented is the average value of strength. For concrete made with OPC first strength test was made after approximately 10-12 hours when the concrete could have been de-molded without damaging the specimen.

3. RESULTS AND DISCUSSION

Fundamental hypothesis of AU approach states that in brittle or quasi-brittle materials greater stress or strain energy flow corresponds to higher strength and fracture resistance so the purpose of AU testing is to evaluate relative efficiency of stress wave energy propagation [5]. This evaluation is done on the basis of stress wave factors (SWF) which are extracted from the waveform. The dominant effect measured in AU is relative attenuation and lower values of SWF generally correspond to regions of higher attenuation [5]. AU measurements started approximately 1 hour after mixing. Changes in AU signals were continuously recorded up to the first 7 days of hydration. As an example waveforms recorded in AU measurement for concrete mix BI-0.4 after 6, 12 and 48 hours are presented in Figure 5. From figure 5 it is visible that amplitude of the waveform increases with increasing age of the specimen tested.

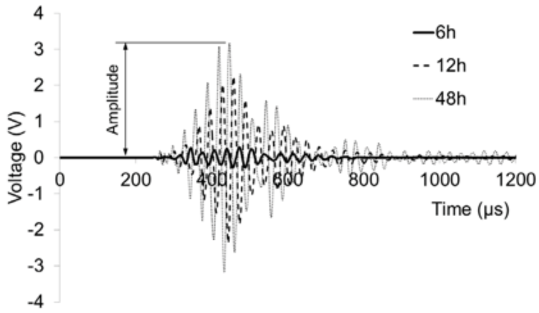

Figure 5 *Waveforms recorded for mixture BI-0.4 at an age of concrete of 6h, 12h and 48h*

From figure 4a) and 5 it can be noted that waveforms contain a part of the signal that could be attributed to a combination of potential reflection arrivals and the so-called ringdown characteristics of AE sensors. Although this affects features extracted from the waveform using the same sensors and testing setup throughout the experiment enables us to attribute changes in waveform characteristics to changes in material properties.

3.1 Amplitude and strength development

Compressive strength development is presented in Figure 6. Average value of 3 results is plotted on the graph. Experimental data of compressive strength is fitted using 3-parameter exponential model (equation 1):

$$f_c(t) = f_u \cdot e^{-\left(\frac{\tau}{t}\right)^{\beta}} \qquad (1)$$

where $f_c(t)$ is compressive strength at an age t, f_u is ultimate compressive strength, τ is a time parameter and β is a slope parameter. From the figure it can be seen that models obtained by fitting can well describe compressive strength development.

Two parameters (SWF) extracted from the waveform showed trend similar to compressive strength development:

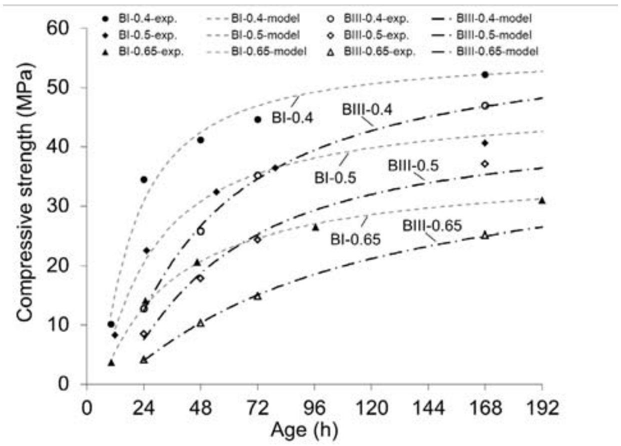

Figure 6 *Compressive strength development measured and modeled with exponential model amplitude and signal strength*

Calculation of signal strength takes into account entire waveform it also contains reflection-ringdown part of the signal. Amplitude of the waveform is less influenced by these effects and therefore is more influenced by changes in material properties. Changes in the amplitude of the waveform recorded for mixtures BI-0.5 and BIII-0.5 are shown in figure 7.

In Figure 7a) amplitude is expressed in volts but in AU measurements it is usually better to normalize these values for comparison with material property variation [5]. It was already discussed how energy transfer of ultrasonic wave across interface is highly dependent on presence of microscopically sized air voids [7]. Amplitude of the ultrasonic wave is also very sensitive to the quality of the contact between sensors and the surface of the tested material. To overcome or at least to reduce impact of this effect on interpretation of a measurement results a way to normalize amplitude is proposed. Shape of the amplitude curve from figure 7 shows that amplitude tends to some asymptotic value so this asymptotic value is used to obtain relative amplitude by dividing measured amplitude with its asymptotic value. Therefore values of relative amplitude will fall within the interval between 0 and 1. It was found that a good fit of experimental data can be made with 3-parameter exponential model which is also plotted in figure 7a) (equation 2).

$$A(t) = A_u \cdot e^{-\left(\frac{\tau_A}{t}\right)^{\beta_A}} \qquad (2)$$

In equation 2 $A(t)$ is the value of the amplitude at age t, A_u is the ultimate amplitude, τ_A is time parameter and β_A is slope parameter. Plot of relative amplitudes for mixtures BI-0.5 and BIII-0.5 and comparison with strength development is presented in Figure 7b).

Because trend of the amplitude development seemed similar to the trend of compressive strength development correlation of these two parameters is investigated. In Figure 8 correlations between compressive strength and relative amplitude are presented. In figure 8a) correlation for mixtures made with OPC is presented and in figure 8b) for mixtures made with CEM III.

This correlation can be very accurately described by linear function which is also presented on the figures.

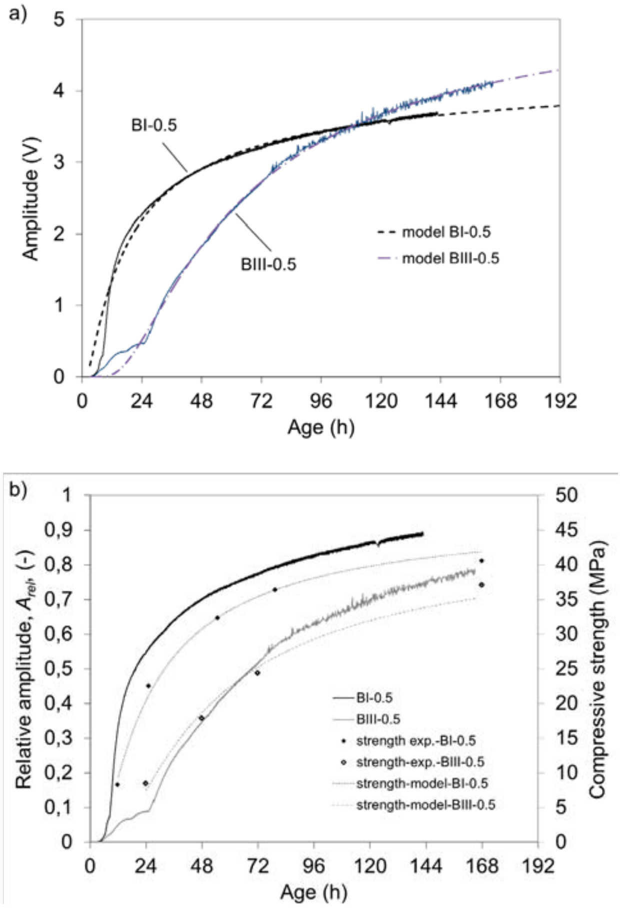

Figure 7 *Changes in the amplitude of waveform for samples from mix BI-0.5 and BIII-0.5: a) absolute values; b) relative values and comparison with compressive strength development*

3.2 Amplitude and UPV development

UPV development in specimens from mixtures BI-0.5 and BIII-0.5 is presented in Figure 9. On the same Figure UPV development is compared to the relative amplitude evolution. From Figure 9 it can be seen that UPV and amplitude have different trend of changing during the first few days of hydration. For mixtures made with OPC velocity increases very fast in the first 12-24 hours and after that period changes only slightly.

Evolution of UPV in mixtures made with CEM III is slower comparing to the OPC mixtures. Largest increase happened during the first 24 hours probably due to hydration of Portland cement. After approximately 24 hours UPV has a second increase which can be attributed to the slag reactions

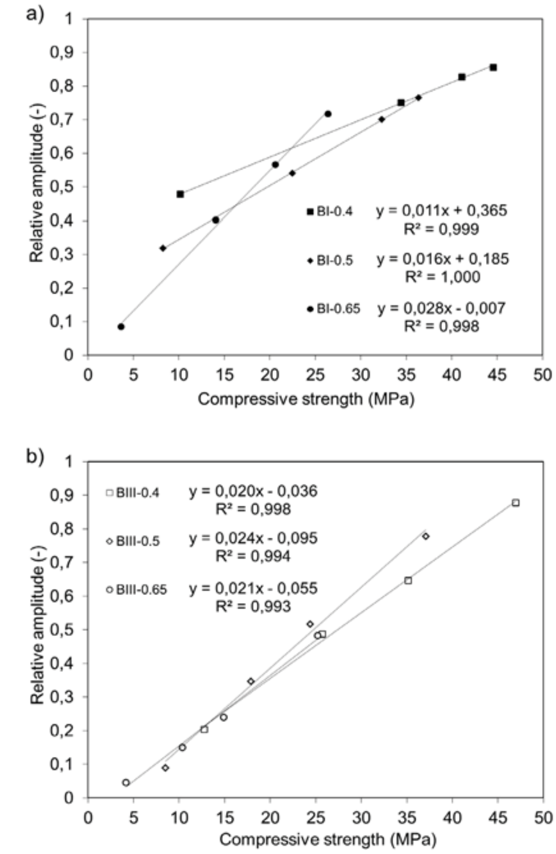

Figure 8 *Correlation between relative amplitude and compressive strength for a) mixtures made with OPC; b) mixtures made with CEM III*

which is activated by the presence of alkaline solution [8].

It was found that L-wave velocity starts to increase before amplitude. Voigt et al. [9]

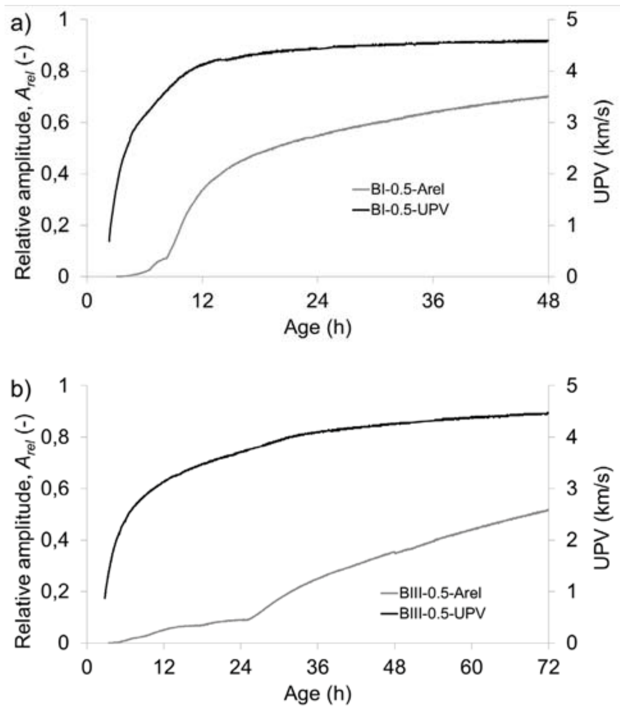

Figure 9 *Comparison of relative amplitude and UPV evolution: a) BI-0.5; b) BIII-0.5*

found that L-wave velocity starts to increase before any changes in the compressive strength and changes of the S-wave could be detected. This phenomenon was attributed to the ettringite needles formed outside the unhydrated cement grains which fill the pore space previously occupied with water.

4. CONCLUSIONS

Monitoring of changes in the waveform of the ultrasonic signal transmitted through the concrete during the first days of hydration was applied for analysis of strength development. It was found that amplitude of the waveform and compressive strength have similar trend of increasing with age of concrete (figure 9) at least until the age of 7 days. Correlation between relative amplitude and compressive strength can be very accurately described by linear equation (figure 10). From the results presented it seems that increase of amplitude of ultrasonic wave transmitted through the concrete sample is governed by the similar mechanism as compressive strength development. Therefore amplitude of the ultrasonic signal could serve as a tool for evaluation of strength at a certain age. Furthermore because correlation is practically linear for the first 7 days it is not unreasonable to presume that correlation could be linear and from that point on so amplitude could also serve as a tool for prediction of strength at a later age for example at 28 days.

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