COMPARATIVE EVALUATION OF CEMENTITIOUS MATERIALS ON EARLY AGE WITH ULTRASONIC WAVE TRANSMISSION, WAVE REFLECTION AND IMPACT-ECHO MEASUREMENTS

VERGLEICHENDE UNTERSUCHUNG DES ERSTARRUNGS- UND ERHÄRTUNGSVERLAUFS VON ZEMENTGEBUNDENEN MATERIALIEN MIT DER ULTRASCHALL TRANSMSSIONS METHODE, DER ULTRASCHALLREFLEXIONSTECHNIK UND DEM IMPACT-ECHO-VERFAHREN

INVESTIGATION COMPARATIVE DE MATERIAUX DU CEMENT AVEC LES METHODES ULTRASONIC A TRANSMISSION, ULTRASONIC A REFLEXION ET IMPACT-ECHO

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SUMMARY

This paper summarizes results of investigations dealing with the setting and hardening of mortar and concrete. Data of three different ultrasonic methods are compared and set into relation to the temperature measured inside the tested elements.

ZUSAMMENFASSUNG

Der Artikel beschreibt die Ergebnisse einer Untersuchung über das Erstarrungsverhalten von Mörtel und Beton mit verschiedenen Ultraschallverfahren und stellt einen Vergleich zu dem im Bauteil gemessenen Temperaturverlauf bei der Erhärtung her.

RESUME

Cet article présente les résultats d’une étude effectuée sur la processus de durcissement des matériaux cimentaires avec les methodes ultrasonic á transmission, ultrasonic á reflexion et impact-echo. De plus il compares les résultats avec les températures mesurée par l’ élément testé.

KEYWORDS: Non-destructive testing, early age concrete,
ultrasonic transmission, WRF, impact-echo.

1 INTRODUCTION

Numerous applications for non-destructive testing methods to investigate concrete structures are reported; they usually focus on the detection of flaws and the determination of concrete thickness. These methods are applied to constructions which are already in service. If there is a demand for quality control at early ages of structures, e.g. for the quality of the used concrete mixture, different or modified methods have to be applied.

During the last years, several testing methods were developed to control the manufacturing process of cement-based materials during setting and hardening. At the Institute of Construction Materials, University of Stuttgart, a through-transmission technique based on ultrasound was developed [2, 4]. This technique correlates the travel time, the attenuation and the frequency content of ultrasound waves sent through the material with the elastic properties of concrete or mortar. These parameters are continuously monitored during the setting and hardening of the cementitious material giving a comprehensive picture instead of snapshots of material characteristics at specific times. The through-transmission technique requires access to both sides of the material to enable a wave travelling through the material. To avoid this disadvantage the impact-echo method was modified, to monitor the hydration process with only one-sided access. This procedure was first suggested by Pessiki et al. [7, 8].

The third method, used for this investigation, is the wave reflection method WRF [5, 6]. In order to increase the sensitivity of the ultrasonic measurement, Öztürk [6] improved the wave reflection test setup that he had developed together with J. S. Popovics at the ACBM-Center, Northwestern University, Evanston [5]. The WRF evaluates the reflected part of the wave, which was incident upon the boundary between a known material, e.g. acrylic glass, and the material to be investigated, e.g. concrete. At concrete the hydration process increases its acoustic impedance leading to a change of the WRF value with time.

This paper reports on results of tests accomplished within the research project FOR 384 [11]. Ultrasonic wave transmission, impact-echo and WRF methods were used to determine setting and hardening process of mortar and concrete. In addition a shear wave transducer was mounted at the surface of the specimen, to measure the shear wave parts of the impact generated waves along the surface. Supplemental to these experiments the in-situ temperature was measured inside the specimen. Depending on the chosen method, the setting and hardening process of tested materials is related in different ways.

2 EXPERIMENTAL METHODS

The wave **transmission method** used for the experiments allows monitoring the setting behaviour of fresh mortar and concrete. For this method a sample of the mixture under test is poured into a container with attached ultrasonic transducers. The elastic wave travelled through the material is recorded. Using a time of flight measurement technique the P-wave velocity can be calculated. In addition the relative energy of the signal and the frequency spectrum can be determined. Further details about this test setup and its application are given in [2, 4, 9].

The **impact-echo method** uses transient stress waves generated by an elastic impact (fig. 1) on the surface of concrete structures. As the stress waves propagate through the material, they are reflected by internal interfaces (e. g. voids and tendon ducts) and external boundaries of the structure. Multiple reflections between the impact surface, internal interfaces and the opposite surface cause transient resonances, which can be identified in the spectrum of the recorded signals. The emitted sound waves are obtained by a displacement or acceleration transducer which is placed near the impact point on the surface of the structure.

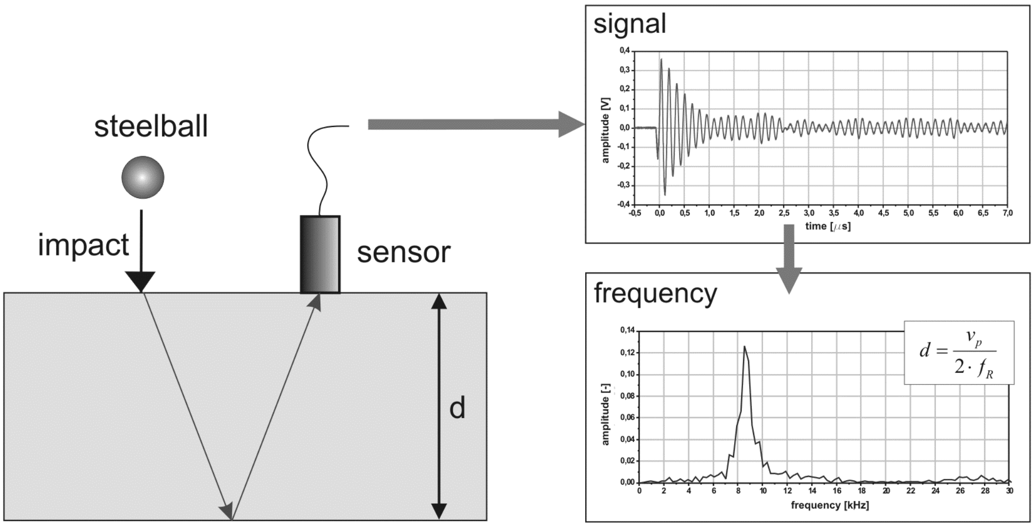

Fig. 1: Impact-echo principle

The depth of interfaces can be determined by analysing the frequency spectrum of signals using following equation

$$d = \frac{v_P}{2 \cdot f_R} \text{ [m]} \quad (1)$$

where d is the depth of the interface (thickness of the structure), v_P is the measured compressional wave velocity and f_R is the corresponding resonance frequency in the spectrum. To apply this technique to fresh concrete several assumptions and changes are necessary. As a first approach it can be considered that the tested material is changing only its rheologic properties and not its geometry. If the thickness is constant, Eq. 1 can be transformed to

$$f_R(t) = \frac{v_P(t)}{2 \cdot d} \text{ [kHz]} \tag{2}$$

where $v_p(t)$ is the compressional wave velocity subjected to changes (usually increasing) during the hardening of tested materials. Therefore, the changing resonance frequency $f_r(t)$ gives an indirect information about the elastic properties of the hardening material.

The test setup for the **WRF** measurements is shown in Figure 2. Normal-incidence P-wave transducer type DEUTSCH S40HB0.1-0.3 with a centre frequency of 200 kHz was used. The transducer was coupled on the acrylic glass plate with a thin layer of VASELINE$^{®}$. The WRF sensor was integrated into the formwork.

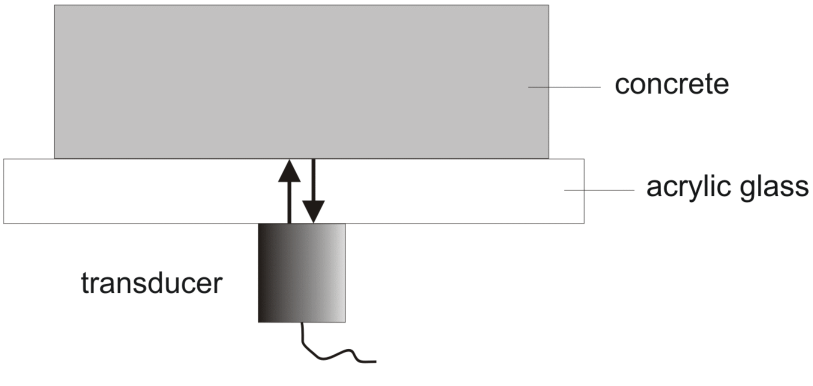

Fig. 2: WRF principle

At an interface between two materials with differing acoustic impedances, a portion of the incident wave energy is transmitted through the boundary into the second material and the remaining is reflected back into the first one. When the propagating wave is normally-incident upon the boundary, the ratio of the amplitude of the reflected wave to the incident amplitude is given by

$$R(t) = \frac{Z_2(t) - Z_1}{Z_2(t) + Z_1}; \quad Z_i = \rho_i * v_{P,i}(t) \tag{3}$$

where R is the reflection factor, Z_1 the acoustic impedance of first material, Z_2 the acoustic impedance of second material, ρ the density of the material and v_P the ultrasonic velocity of the primary wave in the material. As the first material acrylic glass was chosen and the second material was the cement-based material.

A time domain signal analysis was applied. The first received backwall echo was windowed and the absolute value of its amplitude was taken eliminating the phase of the signal. In order to eliminate the influence of the measuring device and the coupling condition of the transducer, the results obtained from the measurements at cement pastes were normalised on that at air and the wave reflection factor was obtained as

$$\mathrm{WRF}(t) = \left| \frac{R_{\mathrm{Concrete}}(t)}{R_{\mathrm{Air}}} \right| \tag{4}$$

where R_{Concrete} is the reflection factor of the acrylic glass – concrete interface and R_{Air} the reflection factor of the acrylic glass – air interface. For this purpose a wave reflection measurement was performed on the empty mould before filling the concrete in. Successively the measurements at the concrete were started and data collection and analysis were performed automatically. The interval for the data collection was set to 10 minutes.

The **shear waves** were recorded by an S-wave transducer consisting of a sensor array. After filling the mixture into formwork, the transducer was fixed on a small plexiglass plate which was mounted at the impact surface with a distance of about 30 cm to the impactor. So we were able to measure the shear wave part of the impact generated waves along the surface.

3 TEST PROGRAMME

The mix proportions of the mortar and concrete tested are given in Table 1. In total one mortar and two concrete mixtures were tested. After mixing the cement or concrete mixture, respectively, and pouring it into formwork the measurements were started (fig. 3, 4). The formwork had a dimension of 80 x 80 cm² and the slabs had a thickness of 15 cm.

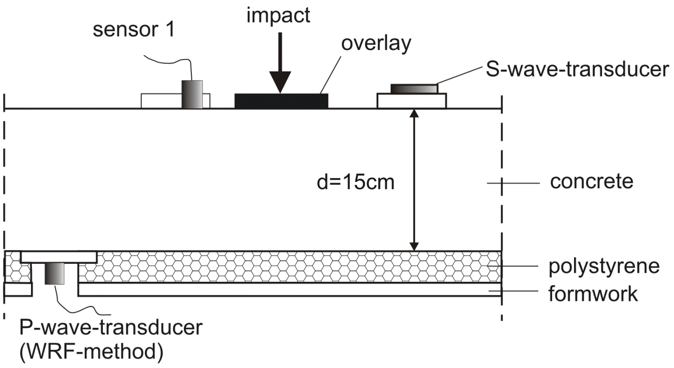

Fig. 3: Measuring setup

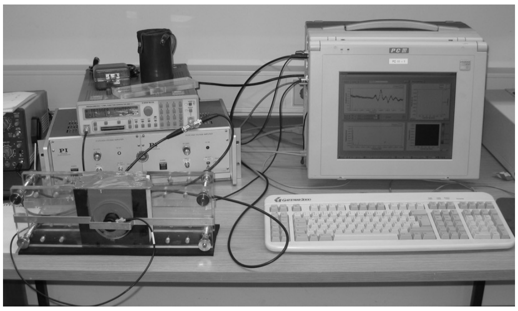

Fig. 4: Measuring setup FreshCon

To determine the temperature variations a thermocouple element was set in the tested specimens. The investigations were accomplished over a period of about 24 hours. Ultrasound signals were recorded every ten minutes.

Tab. 1: Mix proportions

	RS01	**RS02**	**RS03**
cement type	CEMII 42,5R A-LL	CEMII 42,5R A-LL	CEMII 42,5R A-LL
cement	380 kg/m³	380 kg/m³	380 kg/m³
w/c-ratio	0,6	0,6	0,45
gravel max size	2 mm	16 mm	16 mm
superplasticizer	0,2 %	-	0,2 %

The following sections describe and compare the results of the different setups using WRF, ultrasonic transmission and impact-echo methods in concern to their information about the setting process.

4 RESULTS

An important indicator of the cement hydration is the development of the temperature, which is a result of the exothermic reaction between water and cement. Figure 5 shows the results of the in-situ temperatur measurements in comparison to the P-wave velocity obtained with the transmission method.

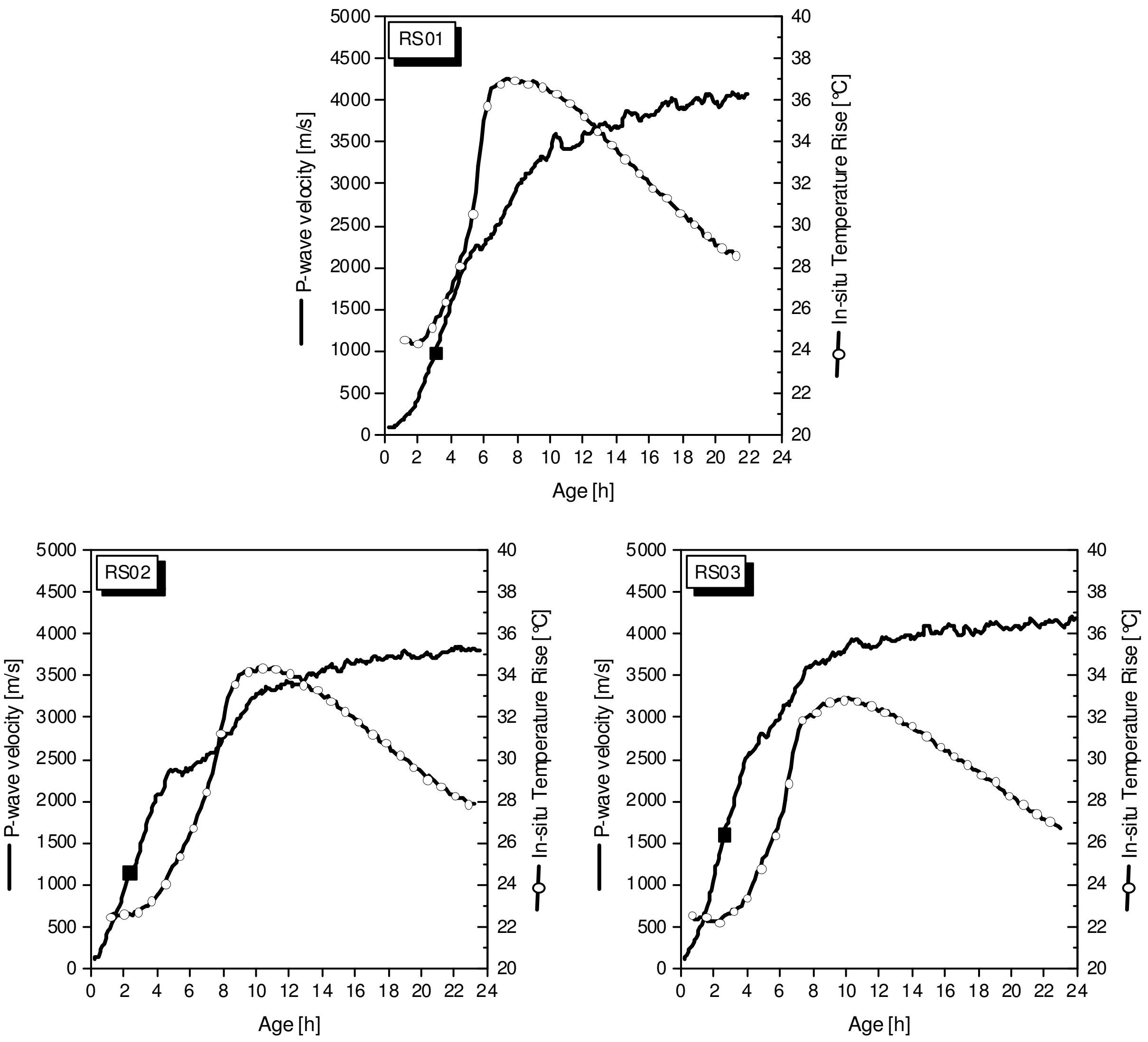

Fig. 5: Comparison between P-wave velocity and in-situ temprature for mortar (RS01) and concrete (RS02, RS03); Inflection points marked as black rectangles on the P-wave velocity curves

The diagrams in figure 5 show that an increase of the P-Wave curve can be observed directly after the beginning of the measurement. In comparison the temperature rises not until the first two hours. The temperatur starts to increase at approximatly the same time when the P-wave velocity has the highest rate of change (inflection point). Furthermore, the temperature curve of the tested concrete mixtures reaches its maximum at a concrete age, when the P-wave velocity has reached a value of about 90 percent of the final value of the entire curve. Afterwards the P-wave velocity increases much slower and reaches the final value at the end of the measurement after 24 hours. It should be noted that for determing the inflection point on the experimantal curves a curve fitting was applied.

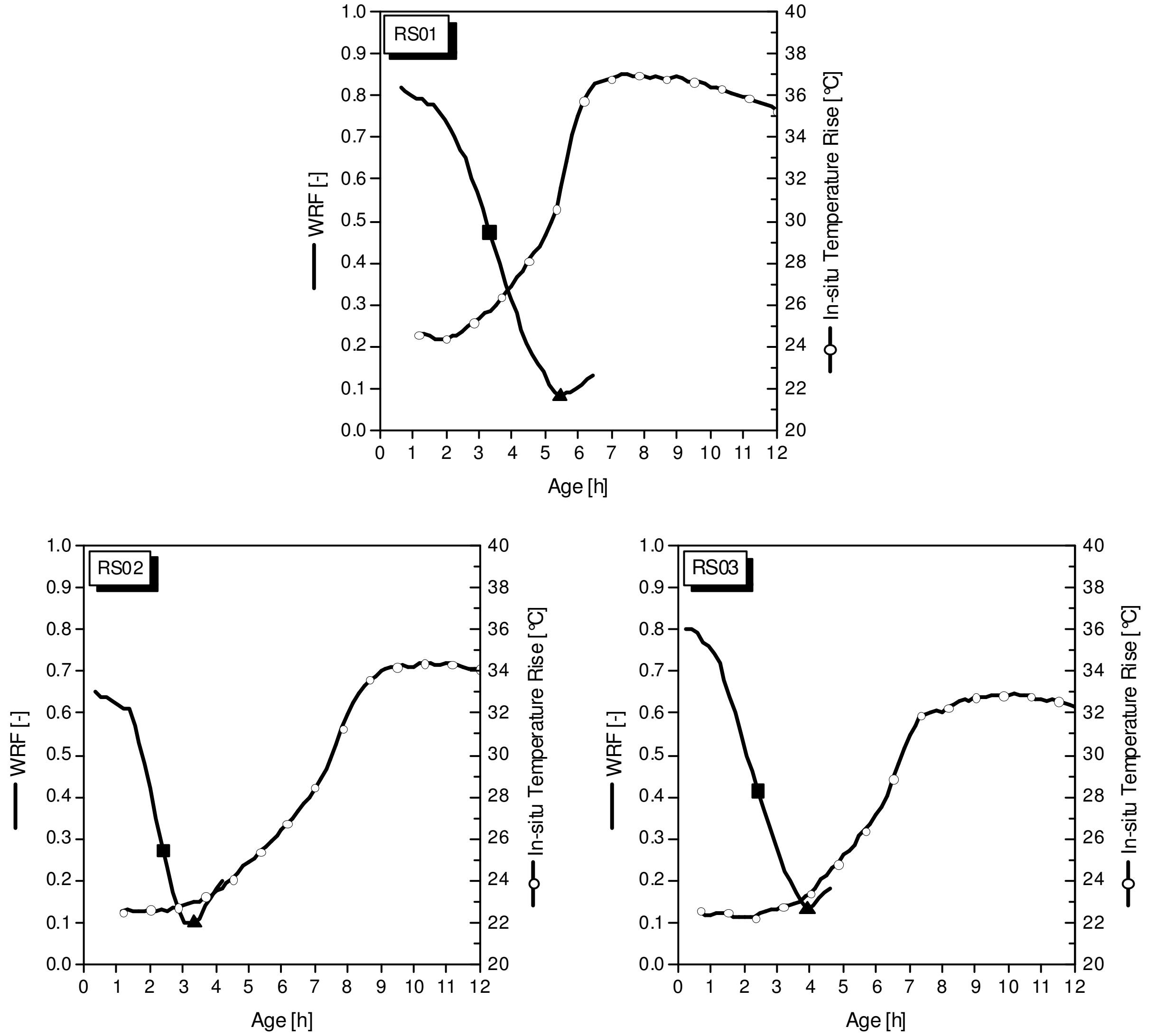

Fig. 6: Comparison of Wave-Reflection-Factor (WRF) and in-situ temprature rise for mortar (RS01) and concretes (RS02, RS03); Times for initial set marked as black rectangles and final set marked as triangles on the WRF curves

Figure 6 shows the development of the WRF and that of the temperature inside the specimen with time for mortar (RS01) and concrete (RS02, RS03). After a specific time elapse the WRF decreases rapidly, has an inflection point, reaches a minimum and increases again. Immediately after mixing, the acoustic impedance of the cement-based material is lower than that of acrylic glass, but increases in the course of the hydration process of the cement. At the minimum of the WRF curve, the acoustic impedance of the cement-based material is equal to that of the acrylic glass. Afterwards the acoustic impedance of the cement-based material exceeds that of the acrylic glass.

At the investigation performed on mortar as well as on concrete the inflection point occurs later than the rise of the temperature curve. This is reasonable for the beginning of the exothermal reaction is accompanied by the initial set just in case of cement paste. At mortar and concrete the occurrence of the initial set takes place after a specific time elapse.

In Öztürk [6] it was shown that the inflection point does not primarily correlate to the beginning of the exothermal reaction, but to the specific mechanical state of the specimen. The inflection point was found to match with the initial set of cement paste, mortar and concrete. This point was considered as the percolation threshold, where the system changes from a suspension of cement particles in water into an interconnected solid phase. The final set time was found to coincide with the increase of the WRF curve after having reached its minimum.

The S-wave velocity of the two concrete mixtures is plotted in figure 7. In comparison to the P-wave velocity, where the curve increase immediately, a significant increase of the S-Wave curve begins later at about 2 hours after mixing. This is due to the fact that for the propagation of S-waves certain shear strength is necessary. The hydration of the cement has to be in progression so that the cement aggregates are rigidly connected. The S-wave velocity increases when the cement matrix changes from liquid to solid medium. It should be noted that at the beginning the cement mixture is not a pure liquid medium e.g. like water. In fact it is a kind of viscous matrix which is able to propagate longitudinal and transversal coponents of elastic waves. Thus the measured values of S-wave velocity are not zero. Comparing S-Wave velocity and temperatures an increase at the same time of both curves can be determined.

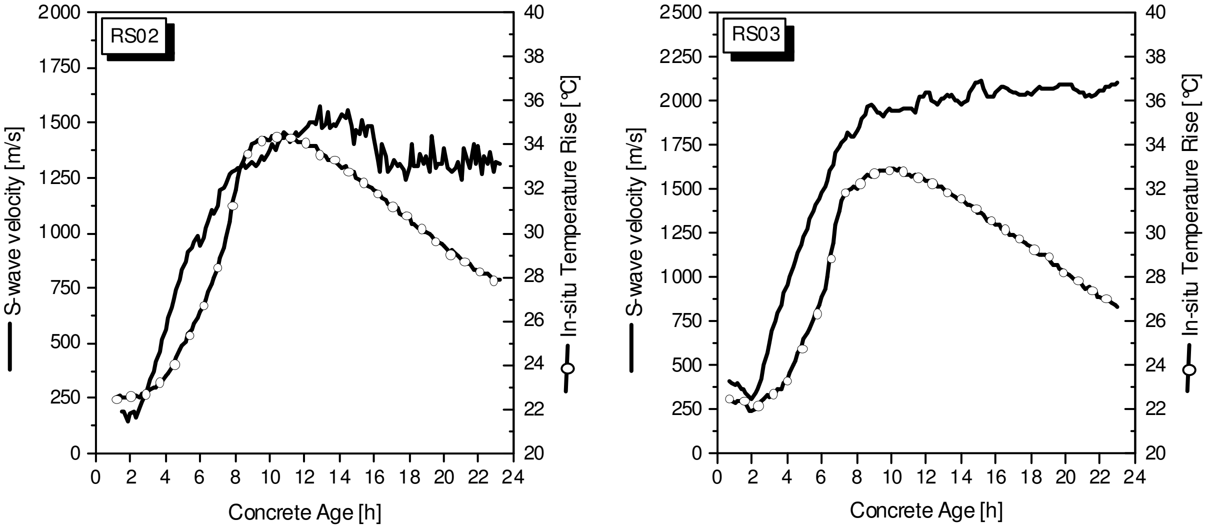

Fig. 7: Comparison of S-wave velocity and in-situ temprature rise for concretes (RS02, RS03)

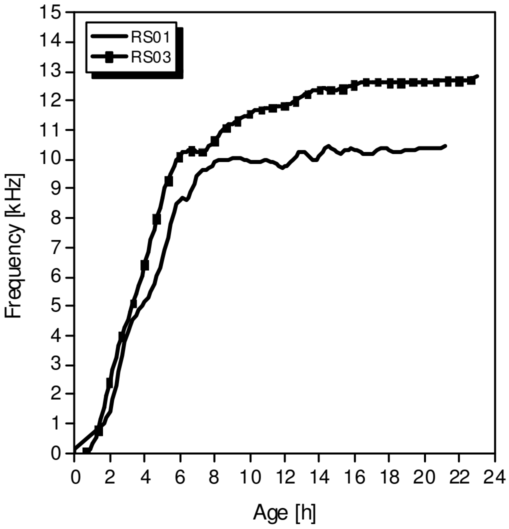

Fig. 8: Resonancefrequency f_R measured by impact-echo (RS01 and RS03)

The maximum amplitudes of the frequency spectra from impact-echo measurements on mortar RS01 and concrete RS03 during setting and hardening are shown in figure 8. Like the developing of the P-wave curve, the curve of the measured resonance frequency starts to increase at the beginning. After about 6 hours there is only a little increase of the curve until a value of the thickness resonance of about 13 kHz can be obtained. Regarding the mixture RS01 the final value is lower than expected due to a loss of sensor coupling.

5 CONCLUSION

The presented investigation shows that the described methods – ultrasonic transmission, wave reflection and impact-echo – have the ability to monitor the setting and hardening of cement based materials. In case of the WRF the setting times can be detected with high accuracy. The data measured on mortar and concrete are related to the in-situ temperature. Regarding the S-wave velocity, it can be seen that an increase at the same time as the temperatures beginns. This indicates that both parameters are governed by the same mechanism, that is the development of exothermic reaction between water and cement resulting in the solidification of the cement paste matrix. Furthermore during this phase, the P-wave velocity and the WRF have reached their inflection point. The accomplished investigations indicate that the parameters of these methods are directly influenced by the cement hydration process.

6 ACKNOLEDGEMENT

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