ABOUT THE IMPROVEMENT OF US MEASUREMENT TECHNIQUES FOR THE QUALITY CONTROL OF FRESH CONCRETE

GERÄTETECHNISCHE FORTSCHRITTE BEI DER QUALITÄTS-SICHERUNG VON FRISCHBETON MIT ULTRASCHALL

AMÉLIORATION DES TECHNIQUES DE MESURE ULTRASONIQUES POUR LE CONTRÔLE DE QUALITÉ DU BÉTON FRAIS.

Christian U. Grosse

ABSTRACT

Over the last decade a testing method based on ultrasound was developed at the Institute of Construction Materials of the University of Stuttgart to control the hardening process of cementitious materials by means of non-destructive testing. This paper describes the systematic improvement and re-design of the testing system and the investigation methods.

ÜBERSICHT

Am Institut für Werkstoffe im Bauwesen der Universität Stuttgart wurde in den letzten zehn Jahren ein Ultraschallverfahren zur die Analyse des Erstarrens und Erhärtens von zementgebundenen Materialien entwickelt. Der Artikel beschreibt die fortdauernde Verbesserung der Messtechnik im Hinblick auf die Qualitätskontrolle von Frischbeton und –mörtel.

RESUME

A l'université de Stuttgart, un procédé ultrasonique de contrôle de la prise et du durcissement des matériaux cimentaires a été développé au courant des dix dernières années. L'article présent décrit l'amélioration continue des dispositifs et de la procédure de mesurage en ce qui concerne le contrôle de la qualité des béton et mortiers frais.

KEYWORDS: Fresh concrete, non-destructive testing, ultrasound

INTRODUCTION

Nowadays the characterization of cement-based materials during the stiffening process by ultrasound measurement techniques is well established. This paper deals with the ultrasound technique used in through transmission. In numerous publications [e. g. GROSSE & REINHARDT 1994, GROSSE ET AL. 1999, REINHARDT ET AL. 1999a] the patented test method [REINHARDT ET AL. 1999b] developed at the University of Stuttgart was described earlier. Methods based on ultrasound are better suited for the characterization of the setting and hardening of cement based materials than traditional test methods like the Vicat-needle-test, the penetrometer test or the flow test, because the travel time, the attenuation and the frequency content of ultrasound waves sent through the material are closely correlated with the elastic properties of concrete or mortar. These parameters can be continuously monitored during the stiffening giving a comprehensive picture instead of snapshots of workability for example.

A sophisticated device was developed and numerous experiments have been conducted in the past, investigating the influence of water-to-cement ratio, the type of cement, the use of additives and admixtures, the air bubble content and so far, for the setting and hardening of concrete or mortar. Newer features are the extraction of the initial and final setting time out of the signals [GROSSE & REINHARDT 2000] and the parallel registration of the state of hydration. However, the earlier described device lacks of handiness and several features, which could improve the art of such measurements further.

EVOLUTION AND SURVEY OF DEVICES EXISTING AT THE UNIVERSITY OF STUTTGART

The first measurements to control the setting and hardening of concrete at the University of Stuttgart using ultrasound are dated back to the early 1990's. These experiments have been conducted in the frame of a research project sponsored by the German Reinforced Concrete Committee (DAfStb, V 345) and are published in the 1994th volume of the Otto-Graf-Journal [GROSSE & REINHARDT 1994]. The tests were carried out with a rough set-up using a container made of 40 mm thick styrene foam (Styropor) plates and the dimensions 300 mm $\times$ 300 mm $\times$ 80 mm (Fig. 1). The emitter was a simple steel ball impactor dropping a ball of 4 mm diameter on to a small aluminium plate, which was placed in contact with the fresh concrete.

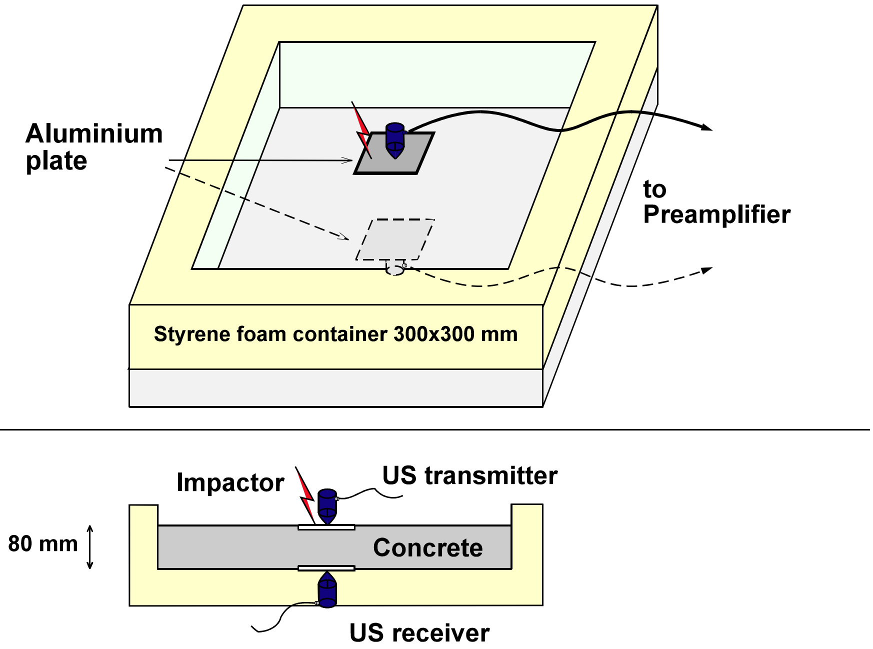


Fig. 1: Set-up with steel ball impactor and receiver.
Dimensions of the container: 300 mm x 300 mm x 80 mm

Later on the ideas were proofed by numerous students during their Diploma thesis, technician and student research assistants. Jochen FISCHER [1994], Bernd Weiler and the author [Grosse 1996] developed a device using three long styrene foam walls and two smaller rigid side walls out of aluminium plates and the same simple impactor as used earlier (Fig. 2).

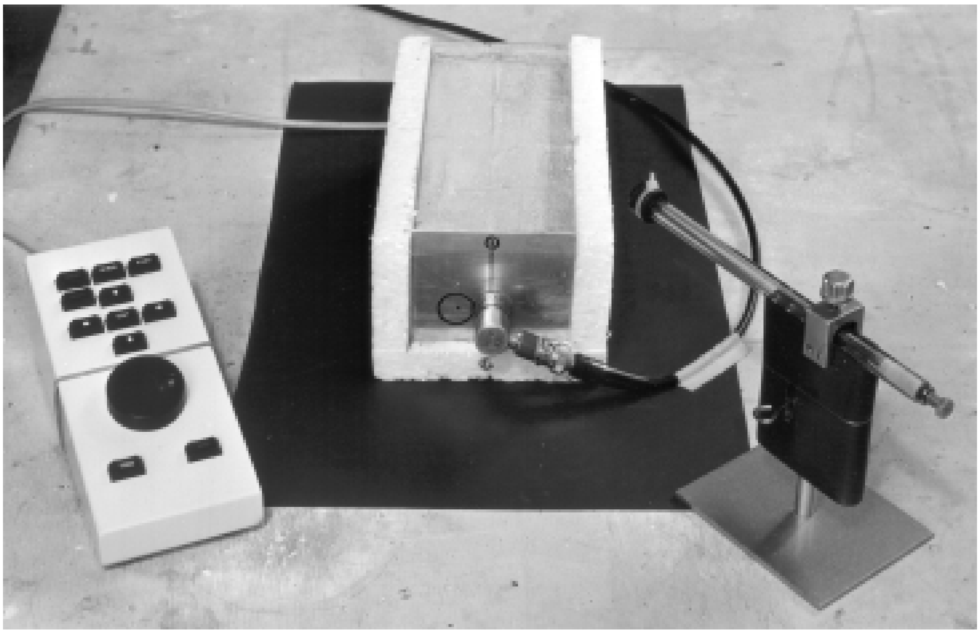


Fig. 2: Set-up of the smaller styrene foam container with two aluminium side walls.
Dimensions of the container: 200 mm x 80 mm x 60 mm.

While the first set-up caused problems to determine the correct travel distance of the pulse to the receiver, what is essential for velocity measurements, the second set-up was unsatisfactory as well, because of interfering waves resulting from the walls.

A re-design of the device described in REINHARDT ET AL. [1996], WINDISCH [1996], HERB [1996] and REINHARDT ET AL. [1998] for concrete measurements was patented later [Reinhardt et al. 1999] and consisted of a mould completely out of PMMA of the dimensions 160 mm × 200 mm × 70 mm (Fig. 3), but the handling of this device was poor and the leakiness of the container caused a penetration of fluids especially during the compaction process. However, the device was modified by BEUTEL [1999] and tested to be suitable for field measurements.

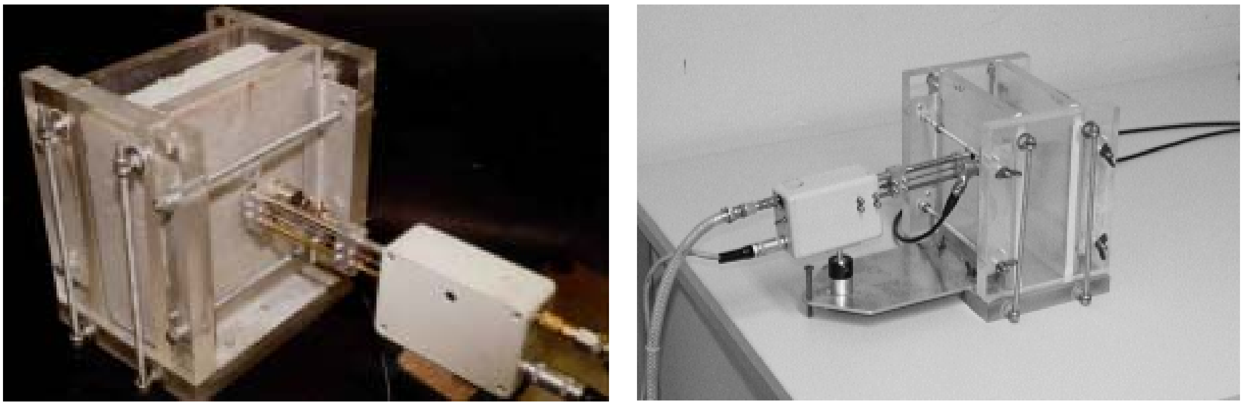


Fig. 3: Set-up of the first container out of PMMA only.
Dimensions of the container: 160 mm x 200 mm x 70 mm.

In the meantime the development of a test set-up adjusted to mortar materials run parallel. Due to smaller grain sizes (usually less 2 mm) the dimensions of a mortar device can significantly be reduced. Not all steps of the development can be described in detail. Figure 4 gives an impression of the iterative process of finding a suitable shape for the mould. The final container [GROSSE ET AL. 1999] had two walls of PMMA and a U-shaped rubber foam with an inner volume of 40 cm³ for the mortar (Fig. 5).

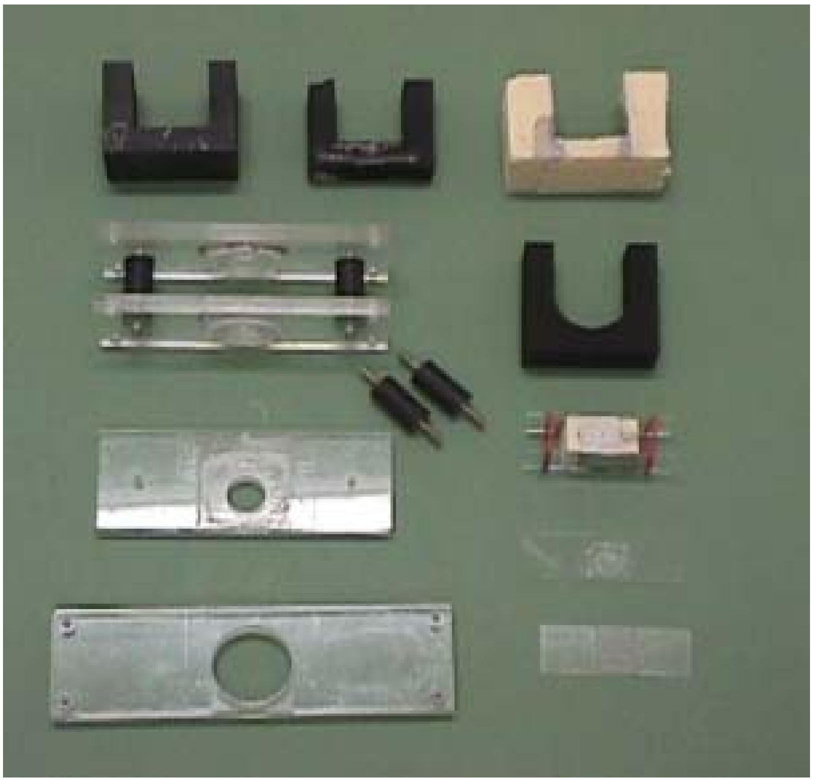


Fig. 4: Evolution of containers, tested for mortar applications.

There are two main advantages in respect to the concrete set-up. The amount of material necessary to be tested is significantly reduced and so is the amount of waste. Secondly, the pulse is not excited by an impactor, what is an advantage in terms of reliability and handiness.

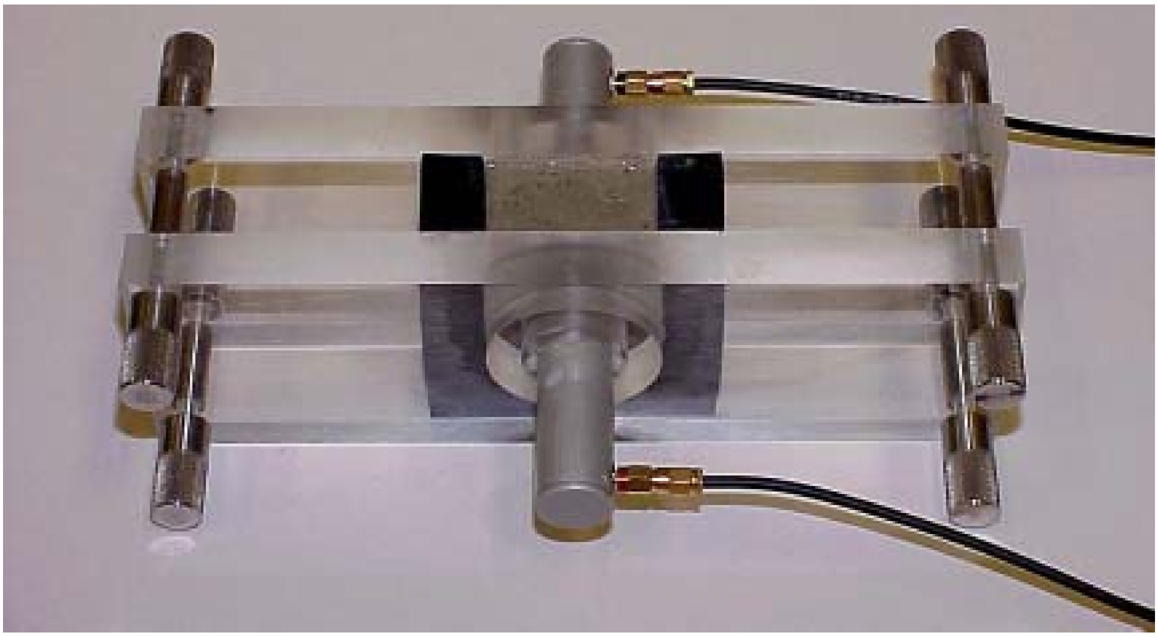


Fig. 5: Final set-up of the mortar device showing the mould (rubber foam and PMMA-walls) and the transducers.

Consequently, a new device, illustrated in Fig. 6, was developed by STEGMAIER [2000] and Herb, whereby the dimensions were changed to 400 mm $\times$ 59 mm $\times$130 mm in accordance to the smaller mortar device. Similar to former concrete devices the wave is generated using a steel ball exciter, referred to as Ultrasound Impactor (USIP), hitting a small plate fixed on the PMMA casing. The resulting excitation can be seen as broad banded, having a relatively wide frequency bandwidth of up to 100 Hz.

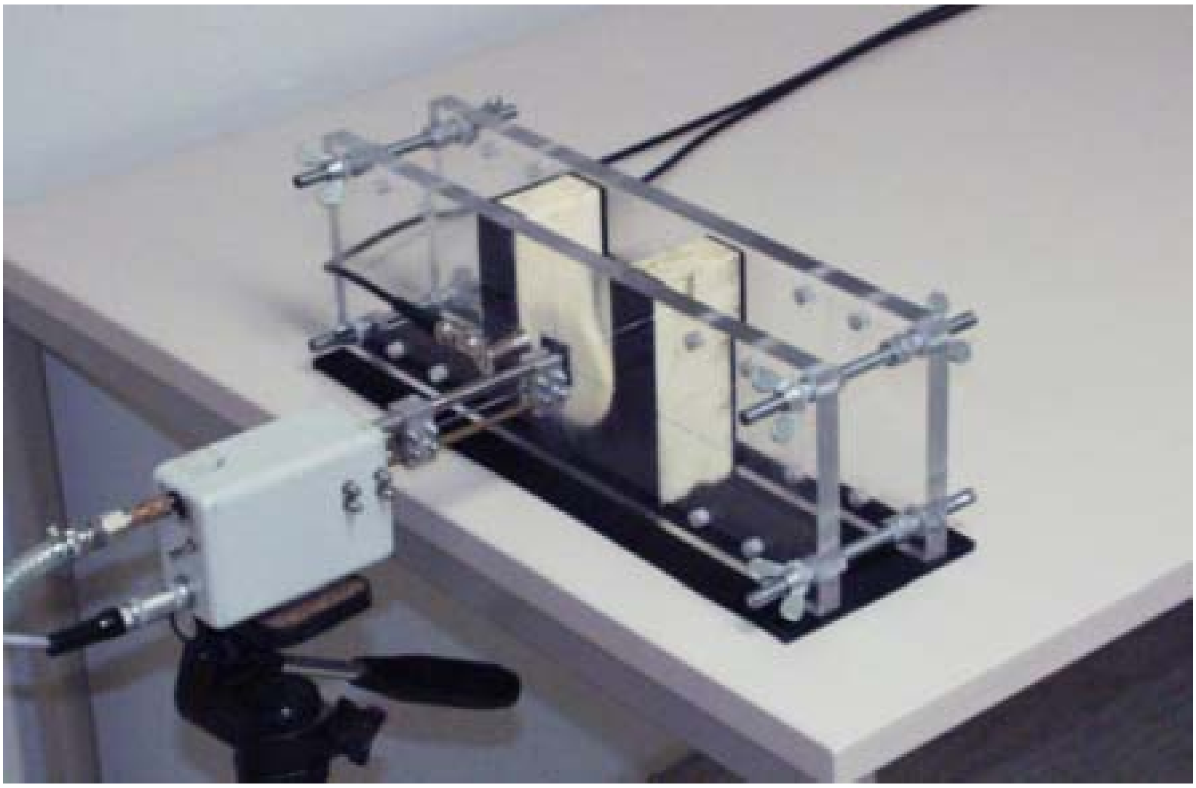


Fig.6: FreshCon device for concrete measurements developed on the basis of the older mortar device (see Fig.5).

Though many difficulties were eliminated the system still shows up unresolved problems. Specifically, a wave travelling through the container wall which onset is detected before the irradiating primary wave can be observed. Further on, the energy evolution during the hardening of concrete is still difficult to analyze since the steel ball transmitter USIP, as a mechanical system, provides unreliable energy data and the plate where the steel ball is shot on easily disbond so that the coupling of the excited energy into the PMMA container changes during tests. These factors influence the obtained results and the reproducibility of tests.

To summarize the pros and cons of the concrete device the following statements can be given:

- Less reproducibility of impact energy results in energy determination uncertainties.
- Contact problems of steel plate at PMMA container (delaminations).
- Unreliable generation of impacts due to steel balls sticking in the impactor rod.
- Possible side wall waves disturbing the measurement at early ages during investigations of very “slow” materials.
- Pressure air equipment necessary for the impactor.

It should be stated, that at the end of 2000 no possibility to record the hydration temperature in the same sample during the ultrasound measurements as a secondary control technique was available using the existing FreshCon software.

ANALYSIS METHODS

Using ultrasound methods the degree of hardening is characterized by the change of significant parameters. Not only the travel time of the ultrasonic pulse through the testing device, consequently the velocity of compressional waves but also the frequency content and the relative energy are recorded.

On the basis of suitable parameters, e.g. the frequency content of the signal over the time, additionally a wavelet transformation (WT) is carried out in order to gather as much information as possible from the raw signal to evaluate concrete and mortar, respectively. The program AutoCWT, able to apply the WT was implemented by MANOCCHIO [2001], where the calculation kernel is taken from the program IWB-CWT, coded by BAHR [2001a]. More information about the application of wavelets in the characterization of the setting and hardening of cementitious materials can be obtained from Grosse [2001], GROSSE & REINHARDT [2001] or MANOCCHIO [2001].

Further on as a new feature of the FreshCon system the ability to record the temperature evolution over the time is introduced as well as the determination of the associated hydration heat, following DIN-EN 196 part 9.

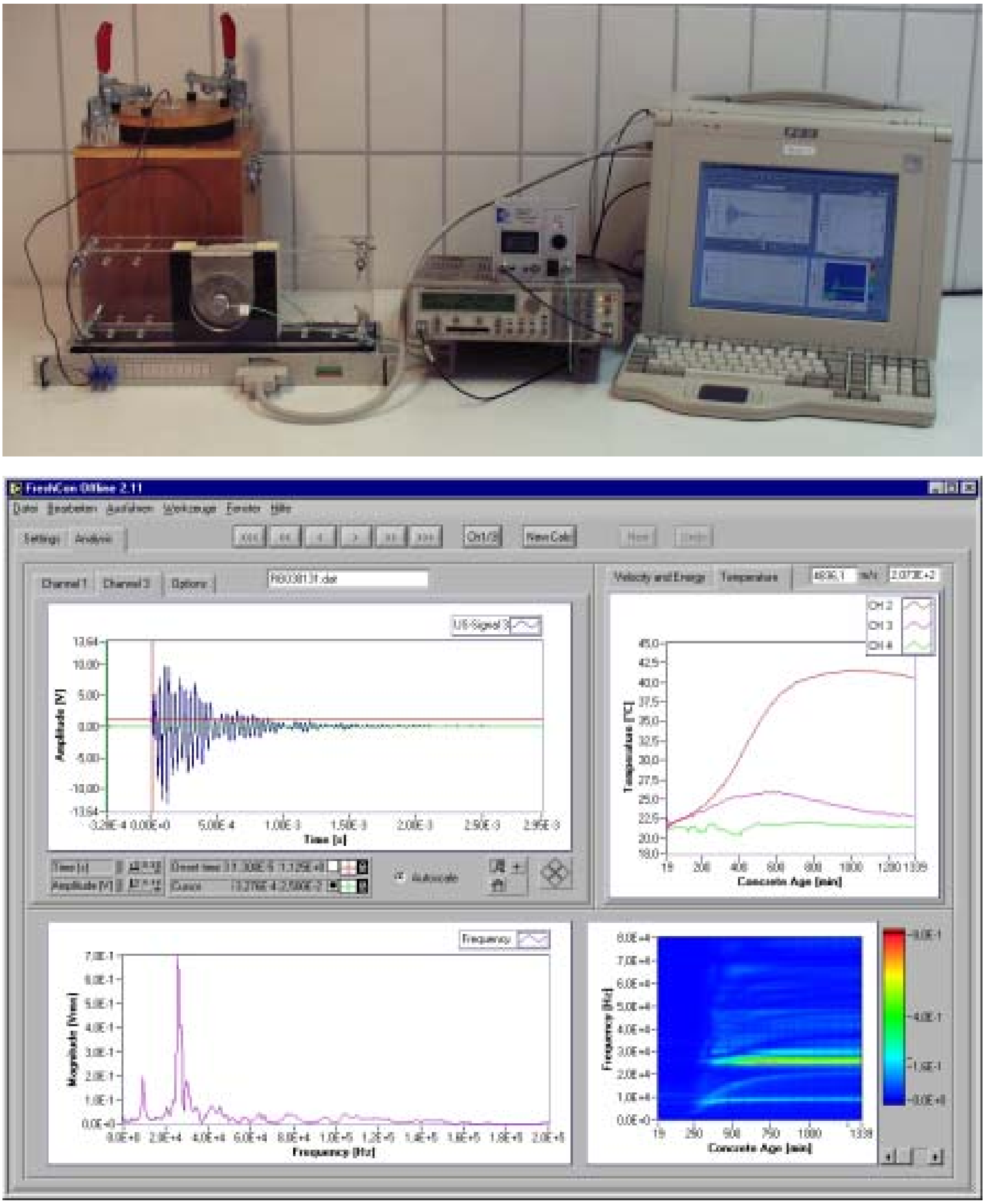


Fig. 7: Set-up (top) for measurements of elastic parameters (velocity, energy, frequency) as well as the temperatures. Bottom: Screenshot of the new program version 2.04 of FreshCon.

MEASUREMENTS OF HYDRATION TEMPERATURES

The program FreshCon was extended to enable temperature measurements using the multi-channel National instrument computer board NI 4351. A screenshot of this program version is represented in Fig. 7, where also a picture of the test setup is given. The temperature distribution occurring during the hydration process is a characteristic for the state of hardening of cement-based materials. Therefore, statements can be deduced according the relations between two different materials. It should be mentioned that the hydration process in the semi adiabatic container in comparison to the testing device for ultrasound measurements is faster due to the accumulation of heat in the temperature container. Consequently, the sound velocity and temperature distribution cannot be correlated directly. A picture of the testing device for the determination of the heat of hydration, taken from KÖBLE [1999] is given in Fig. 8.

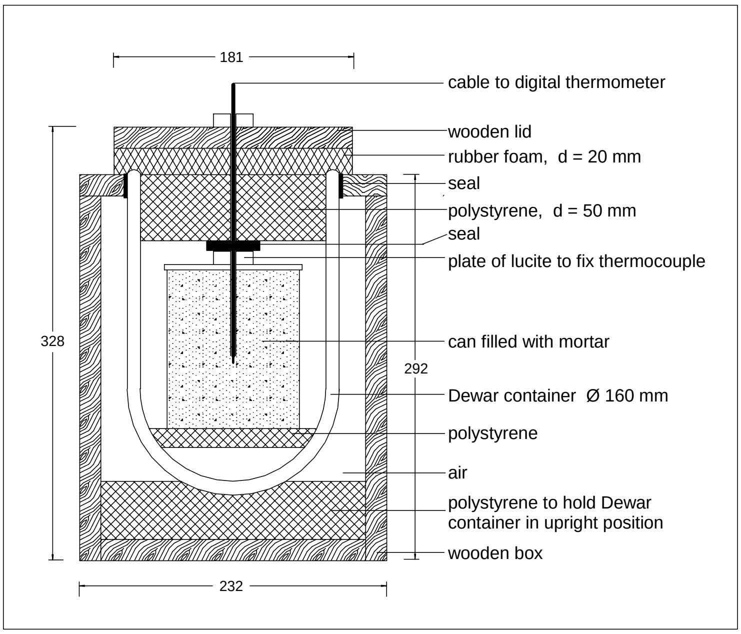


Fig. 8: Set-up of the calorimeter device according KÖBLE [1999], dimensions in mm.

Regarding the determination of the heat of hydration DIN EN 196 - 9 is followed, accordingly. The aim of the semi-adiabatic method, namely the Langavant - method, applicable to mortar, is the determination of the released amount of heat during the hydration process. For this purpose the online version of the program FreshCon, implemented by BAHR [2001b], was modified. The system is now able to record the temperature in the calorimeter (Fig. 8), the temperature in the tested material (Fig. 7, top) and the air temperature. All these data are obtained automatically and stored together with the data of the ultrasound measurements. A typical result is represented in Fig. 9, showing all three temperatures as a function of the concrete age. The temperature effect is dominant at the curve obtained using the calorimeter (straight line) due to the semi-adiabatic conditions in the Dewar container. Testing concrete materials a hydration effect is clearly seen at the temperature data obtained in the ultrasound container (dotted line) compared to the air temperature (dashed line).

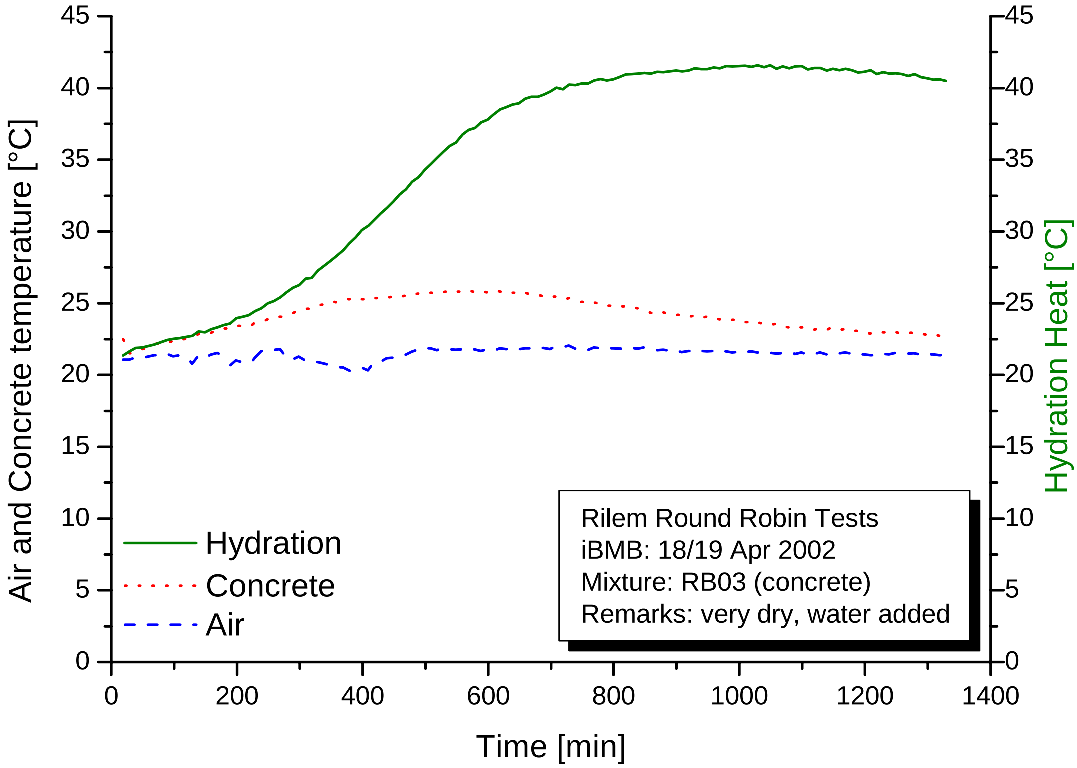


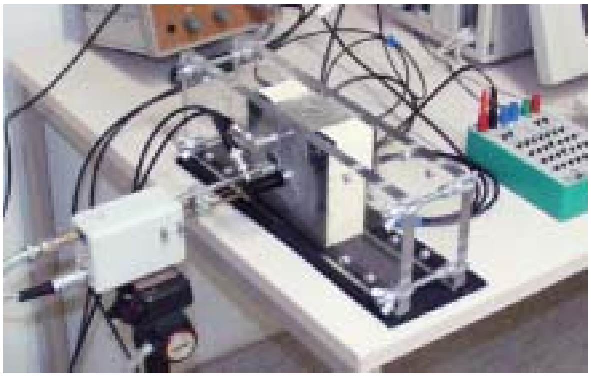
Fig. 9: Results of temperature measurements using the new FreshCon version.

DEVELOPMENT OF A NEW CONCRETE FRESHCON DEVICE

Comparing the two devices for mortar and concrete measurements, the advantages of the mortar set-up should be summarized:

- Good reproducibility of signal generation (energy).
- Easy onset time determination due to signals with good reproducibility.
- No pressure air equipment necessary.
- Full automatic measurement and storing of waveforms.
- Automatic determination of velocity and energy as well as additional parameters.
- Full control of measurement parameters.

To enhance the handling of concrete experiments accordingly, a new design of the device shown in Fig. 6 was suggested. For the new device the impactor was replaced by an US transmitter in combination with a wideband power amplifier and a function generator. No pressure air is need for this device; a control sensor next to the impactor recording the emitting pulse is no longer required.



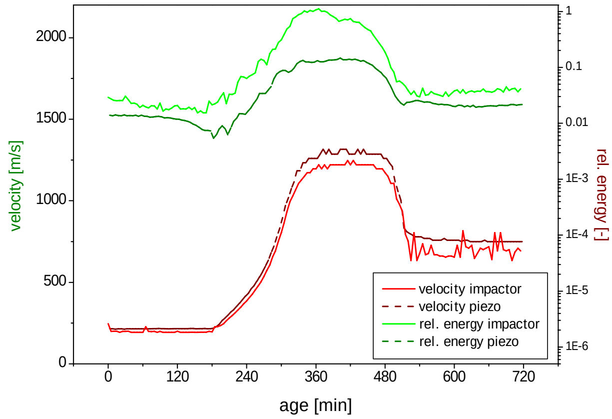


Fig. 10: Comparison experiments between impactor and US emitter.

In several preliminary experiments the new set-up was tested by MANOCCHIO [2001] to compare the results of measurements by the impact generated signals and by piezo-electric emitters in parallel (Fig. 10). The two curves at the bottom of the right side in Fig. 10, recorded at the same time using the same material, represent the velocity evaluation of gypsum. Gypsum was used as a test material due to its fast hydration evolution. The two curves at the top position in Fig. 10 represent the relative energy. A decrease of the velocity and energies values is caused by shrinkage effects. Both curve pairs look very similar in respect to differently used pulse generation methods.

This successful first test triggered the re-design of the concrete device (as well as of the mortar device). A flow chart of the new experimental set-up is given in Fig. 11. The electronic pulse is generated by a frequency generator and amplified by a power amplifier. Broadband piezo-electric transducers generate the ultrasound signal to be transmitted through the material. A transducer of the same type is used as a receiver and the signal is passed through a pre-amplifier to the PC-board A/D-converter, denoted as “computer-based signal processing” in Fig. 11. Special attention is given to the correct trigger time of the signal, what is essential for velocity measurements. A power amplifier of the companies KROHN-HITE CO. or DEVELOGIC GMBH is used along with sensors of the company VALLEN INSTRUMENTS.

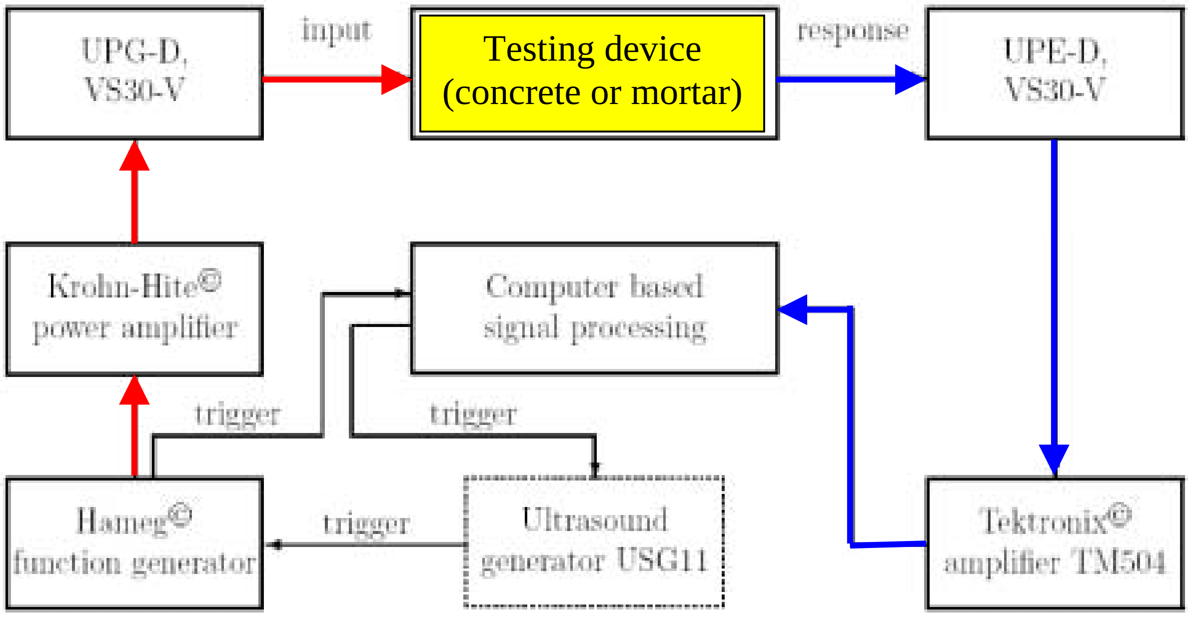


Fig. 11: Flow chart of newly developed FreshCon experiments.

The new container/sensor design for concrete as well as for mortar experiments is shown in Fig. 12, demonstrating the similarity of these two. The U-shaped rubber in the middle of the container is essential. Regarding the concrete device, a special "long wall" container was produced for very "slow" materials to avoid waves propagating along the walls to be faster than the direct waves. The distance of the screw joints can be adjusted to the material properties.

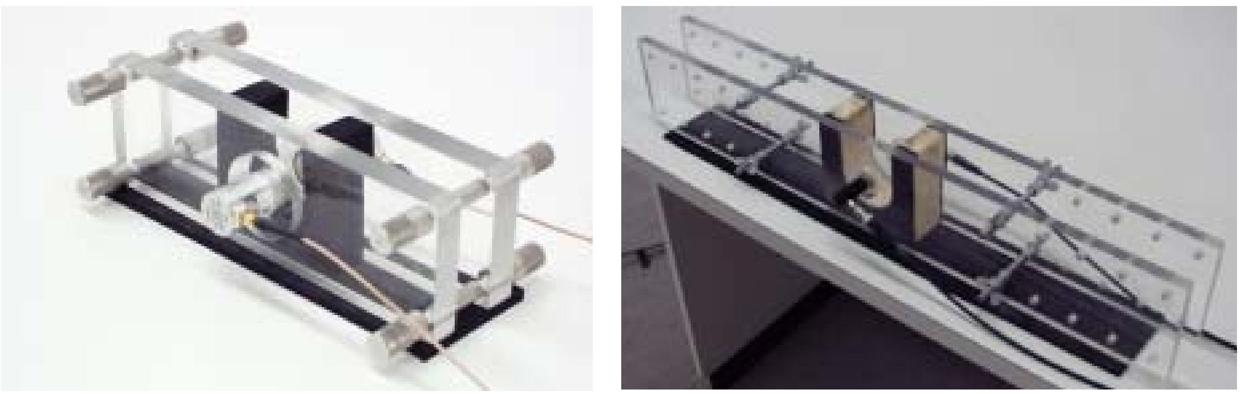


Fig. 12: Re-designed FreshCon container/sensor for mortar (left) and concrete (right) measurements.

First experiments in the frame of a master thesis [KALCKBRENNER 2002] and during round robin test of a RILEM technical committee showed very promising results.

ROUND ROBIN TESTS – STATUS

The International Union of Testing and Research Laboratories for Materials and Structures, RILEM, as a non profit-making, non-governmental technical association is structured in groups of international experts, the so called Technical Committees (TC). In the framework of advanced testing of cement-based materials during setting and hardening the *TC 185 - ATC* organized a round robin test series. The purpose of these tests is to assess the capability of existing test methods based on non-destructive techniques in terms of suitability, sensitivity and accuracy. Results will be summarized in a state of the art report and a test recommendation is planned to be released. In the context of providing a direct comparability, experiments are carried out by different members at the same place using the same charge of materials/mixtures.

The technical realization of the experiments is in the responsibility of the TC secretary (C. Grosse) and the local organizers. The ongoing test series started in 2001 with experiments in Vaulx-en-Velin (France) and was continued in Evanston/Chicago (USA) in spring 2002 and Brunswick (Germany) in summer 2002. The next round robin test is scheduled for spring 2003 in Delft (The Netherlands). In detail the following groups have been involved so far:

- *Ecole Nationale des Travaux Publics de l'Etat* (ENTPE), Vaulx-en-Velin, France; Dr. L. Arnaud and Prof. C. Boutin.
- *Center for Advanced Cement-Based Materials* (ACBM) at Northwestern University, Illinois, USA; Prof. S. Shah and Dipl.-Ing. T. Voigt.
- *Institute of Structural Materials, Solid Structures and Fire Protection* (iBMB) of the Technical University of Brunswick, Germany; Prof. H. Budelmann, Dipl.-Math. M. Krauß.
- *Fraunhofer Institute for Non-Destructive Testing* (IZFP) in Saarbrücken, Germany; Dr. G. Dobmann and Dr. B. Wolter.
- *Institute of Construction Materials* (IWB) at the University of Stuttgart, Germany; Prof. H.-W. Reinhardt, Dr. C. Grosse and Dipl.-Ing. A. Kalck-brenner (M.Sc.).

An experimental test program was compiled to be the basis for all experiments [GROSSE & REINHARDT 2002]. Six different mixtures are recommended to be tested – five other mixtures are tested additionally. Some of the results obtained by the Institute of Construction Materials (IWB) at the

University of Stuttgart are published by KALCKBRENNER [2002] and correlated to the results of other groups. A comprehensive report will follow.

To give an example of the data obtained during one test series Fig. 13 demonstrate the variation of the velocities over the age of the material. Concerning these velocities an S-shaped curve is typical for cementitious materials. After a certain time at the beginning, while the velocity variation is small, the gradient is increasing significantly. Regarding the data RE5 from a mix with added retarder this increase occurs relatively late. To make the basic statements more evident the curves are smoothed and bad data points are removed. It is obvious that concrete mixes are “faster” than mortar mixes in respect to hardening, while the RE5 mix with retarder is the “slowest“ material.

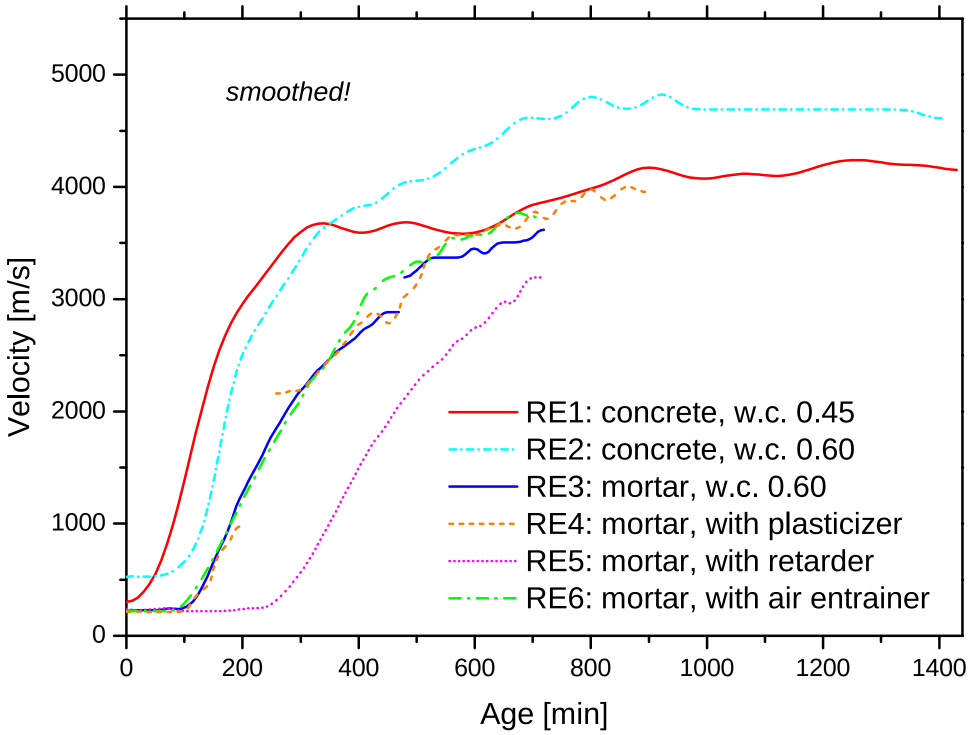


Fig. 13: Comparison of the velocity measurements testing mixtures RE 1-6.

It should be stressed that only material properties related to the elastic behavior can be analyzed with ultrasound techniques. As far as the chemical properties are not related to the elastic properties, other measurement techniques have to be used in combination with ultrasound to get more data. The results of the round robin tests should indicate the value of the described ultrasound through-transmission technique in comparison to other techniques like ultrasound reflection, nuclear magnetic resonance, electric and maturity methods.

SUMMARY AND OUTLOOK

The measuring device developed at the University of Stuttgart is able to analyze the setting and hardening of cementitious materials in a comprehensive way. The method is based on ultrasound and can be used for numerous applications, where reliable and reproducible data are required, what addresses material parameters like the water-to-cement-ratio, the type of cement or the effect of additives as retarders or accelerators. At the concreting site, where efficiency and a low budget are boundary conditions, the application of this new technique can help to enhance the stability during construction or the progress of the construction work saving both: time and money. Some examples are the development of admixtures, the in-situ quality control, the slip form concreting or the precasting. Certainly, the applications are not restricted to cementitious materials.

Further improvements are concerning the velocity evaluation. Since the device consist of an analogue-to-digital converter of 5 MHz only, the resolution of the velocity calculations varies over age. Actually, the resolution decreases with increasing velocities. This is the reason of the so-called bit-pattern occurring usually at ages of 400 minutes and later. To ease the interpretation the velocity curves are smoothed using adjacent averaging (10 points), but it is suggested to plot the original data points into the smoothed curves as well. Using the offline version of the FreshCon picking algorithm the data can be re-evaluated after the test concerning the onset times of the signals only. Surprisingly, curves re-picked by the operator are usually very similar to the automatically processed data so that a time consuming manually picking is not improving the results anymore.

Formerly, the comparison of energy evaluation results was sophisticated due to the application of two different devices. Energy values as measured by the FreshCon software are basing on the squared amplitudes of the signal beginning at the signals onset of compressional waves. These values strongly depend on the energy released by the impact to the container. The reproducibility of the transmitter energy is low of impactor devices compared to devices using an ultrasound emitter. Changing the set-up as described made the interpretations regarding energies more reliable. There is still the disadvantage of energies emitted by piezo-driven devices to be of several magnitudes lower than impactor pulses. A new impactor device without pressure-air giving broad-band pulses of reproducible magnitude is under development.

Talking about the scientific aspects of the ultrasound technique, the method developed at the University of Stuttgart is under further progress. This is especially true concerning wavelet algorithms. The degree of automatization is enhanced and additional analysis techniques will be implemented in future.

With regard to the international activities of the RILEM technical committee more information can be obtained from the author or at the TC's homepage: http://www.rilem.org/atc.html. Colleagues working in this scientific field are offered to collaborate in this initiative.

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