

FRESH CONCRETE MONITORED BY ULTRASOUND METHODS

FRISCHBETONUNTERSUCHUNGEN MIT HILFE VON ULTRASCHALL

EXAMENS ULTRASONIQUES DU BETON FRAIS

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ABSTRACT

While the requirements regarding the quality control of fresh concrete are nowadays increasing, the methods used for monitoring in-situ at the concreting site are lacking in many ways. They are widely used and for a low budget, but can not be used for reproducible and reliable measurements of the setting and hardening of cementitious materials while they are very limited in terms of control parameters. Systematic investigations as well as the increasing number of damages at the concreting site are demanding a new kind of quality management maybe based on ultrasound.

In the last ten years a testing method based on ultrasound was developed at the IWB to control the hardening process of cementitious materials by means of non-destructive testing. It is described how this software called **FRESHCON2** is operating and some examples of data and applications are given.

First results obtained during a round robin test in collaboration with the *Ecole National des Travaux Publics de l'Etat* (ENTPE) in Vaulx-en-Velin near Lyon (France) are shown. This test series was suggested by a Rilem Technical Committee ATC (*Advanced testing of cement-based materials during setting and hardening*) founded in 1999.

ÜBERSICHT

Trotz gestiegener Anforderungen der Qualitätssicherung im Bauwesen, sind die in der Praxis angewandten Verfahren zur Überwachung in vieler Hinsicht ungenügend. Zwar sind sie weit verbreitet und vergleichsweise preiswert, jedoch oft auch sehr ungenau und erlauben nur eine stark eingeschränkte Möglichkeit zur Überwachung der Frischbetoneigenschaften. Systematische Untersuchungen und die wachsende Zahl an Schadensfällen scheinen die Einführung von modernen z. B. ultraschallbasierten Verfahren erforderlich zu machen.

An der Universität Stuttgart wird seit mehr als zehn Jahren die Einsatzmöglichkeit der Ultraschalltechnik im Hinblick auf die Analyse des Erstarrens und Erhärtens von zementgebundenen Materialien untersucht. Neben grundlagenorientierten Arbeiten entstand dabei auch eine Messapparatur (**FRESHCON2**), die den Einsatz des Verfahrens für vielfältige Anwendungsfälle auf Industrieniveau ermöglicht.

Es wird nur kurz auf die Funktionsweise des mittlerweile etablierten Verfahrens eingegangen, da dieses bereits in mehreren Publikationen früher beschrieben wurde. Ausführlicher wird der Stand der internationalen Kooperation, die u. a. eine Vornormungsarbeit darstellt, erläutert, wobei erste Ergebnisse eines Ringversuchs gezeigt werden.

RESUME

Malgré les exigences accrues pour l'assurance de la qualité dans le génie civil, les procédés de surveillance existants sont inappropriés à beaucoup d'égards. Certes, ils sont très répandus et relativement bon marché, mais souvent très inexacts et ne constituent qu'une possibilité fort limitée pour le contrôle des propriétés du béton frais. Des enquêtes systématiques et le nombre croissant de dommages aux constructions montrent le besoin de procédés modernes, basés par exemple sur les ultrasons.

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. En parallèle à la recherche fondamentale, un dispositif de mesure (**FRESHCON2**) permettant l'application de ce procédé à des cas variés au niveau industriel a été réalisé.

Le fonctionnement de ce procédé entre-temps établi n'est décrit que brièvement, car il a déjà été l'objet de diverses publications. L'état de la coopération internationale, qui représente entre autres un travail de pré-normalisation, est exposé en détail et les premiers résultats d'un essai interlaboratoire sont présentés.

KEYWORDS: Fresh concrete, non-destructive testing, ultrasound, wavelets

CONCRETE QUALITY MANAGEMENT – STATE OF THE ART AND FUTURE PROSPECTS

To characterize fresh concrete or mortar at the concreting site nowadays methods are used describing only some parameters of the material, what is true especially for methods investigating the consistency, the workability or the content of air bubbles. They are poor in terms of accuracy, reproducibility and are not satisfying in the frame of a modern quality management system. Some are named as follows:

- Vicat-needle-test according to DIN EN 196 to measure the initial and final setting time of cement paste.
- Penetrometer test according to ASTM C-403 to measure the initial and final setting time of concrete.
- Flow test according to DIN 1048 and slump test according to DIN ISO 4109 to measure the workability of concrete.

All these methods (and there are more) have in common, that they are giving only a momentary picture of the material properties and are not representing details of the whole process of setting and hardening in time. Reliable statements regarding the efficiency of additives continuously monitored during the stiffening can not be obtained.

This is the reason why the authors and several working groups worldwide are working on modern techniques to replace or enhance the methods used today. Methods based on ultrasound are better suited for this purpose, because the travel time, the attenuation and the frequency content of ultrasound waves sent through the material are closely correlated with the elastic properties and especially with the setting and the hardening of concrete or mortar. These parameters can be continuously monitored during the stiffening giving a comprehensive picture instead of snapshots of workability for example. Usually the signals are investigated using the velocity or energy of the compressional waves transmitted through the material. Modern techniques are not only describing the process of aging using single parameters of the ultrasound signals but the whole waveform of each signal in terms of frequency content to enhance the information density. A new approach using the wavelet technology is represented in this paper.

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. The basis is the ultrasound technique used in through transmission. 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.

INTERNATIONAL COOPERATIONS AND PRE-STANDARDIZATION

The long-term research initiative initiated by the authors at the University of Stuttgart is not the only project in this field targeting an improvement of quality control using non-destructive testing. In 1999 the authors established an international committee in the frame of the RILEM organization (*Reunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions*) acting as a chairman (Prof. Dr.-Ing. H.-W. Reinhardt) or as a secretary (Dr.-Ing. Chr. Grosse) respectively. The committee 185-ATC was given the title „Advanced testing of cement-based materials during setting and hardening”. As of 1st of November 2001, there are more than 21 members coming from Denmark, France, Germany, Israel, Japan, The Netherlands, Slovenia, Spain, South Africa, Turkey and the United States. One of the duties of the members is the work on state of the art reports describing the different methods used for this subject in practice and science. The secondary aim is to release recommendations working as pre-norm in regard to international standardization institutions as CEN or ISO.

The methods represented by the committee members are a good cross section of all relevant NDT methods dealing with modern quality control of cementitious materials. These are for instance the nuclear magnetic resonance (NMR) or electric methods, techniques bases on mechanical waves (as ultrasound) used in reflexion or transmission, the acoustic emission technique or maturity methods. It was decided by the committee that all methods have to be proven during a comprehensive round robin test. This is to compare the suitability in regard to quality control, reliability, handling, reproducibility and practicability. To give an impression of the efficiency of the tested methods and

the procedure of the round robin tests some results of the Stuttgart group are represented.

Tab. 1: Overview of the test series - collaboration with the French group at ENTPE.

	Date	w/c	Material	Additive
RE 1	03-07-01	0.45	Standard concrete I; Ø 22	no
RE 2	06-07-01	0.60	Standard concrete II; Ø 22	no
RE 3	10-07-01	0.60	Standard mortar; Ø 2	no
RE 4	12-07-01	0.50	Standard mortar; Ø 2	Plasticizer
RE 5	19-07-01	0.60	Standard mortar; Ø 2	Retarder
RE 6	17-07-01	0.50	Standard mortar; Ø 2	Air entrainer
RE 3B	11-07-01	0.60	Standard mortar; Ø 2	no
RE 7	13-07-01	0.40	Standard mortar; Ø 2	Superplasticizer
RE 8 (RE4B)	16-07-01	0.50	Standard mortar; Ø 2	Plasticizer
RE 9	26-07-01		Standard mortar; Ø 2	Plasticizer
RE 10	20-07-01	0.80	Chalk	no

ROUND ROBIN TESTS – FIRST RESULTS

The first collaboration to do experiments in the frame of round robin tests of the RILEM TC-ATC was agreed between the French and the Stuttgart group. The device developed at the University of Stuttgart was carried by road to Vaulx-en-Velin near Lyon, France. In close cooperation with the group of Dr. Laurent Arnaud and Prof. Claude Boutin from the *Ecole Nationale des Travaux Publics de l'Etat* (ENTPE), a comprehensive experimental program (Tab.1) was conducted, which will be the basis for further experiments during the round robin tests. Six different mixtures are recommended to be tested – additionally five other mixtures have been tested by the Stuttgart group. To give an example, the results of the ultrasound experiments obtained during the hardening of a standard mortar mix according to Tab.2 with added retarder are presented. More results as well as the results of the French group will be published soon elsewhere. A description of the technique used by the colleagues at the ENTPE can be found in the literature [Arnaud & Thinet 1995, Boutin & Arnaud 1995, Arnaud et al. 2000].

Tab. 2: Example of a formulation for mixtures in the round robin tests of the RILEM TC-ATC (RE5).

RE5 Standard Mortar, formulation W/C=0,6 and RETARDING AGENT						
Corrected Water Content		0,6				
	in mass (kg/m ³)		For 70l		For 4l	
	kg	L	Vol (L)	Mass (kg)	Vol (L)	Mass (kg)
cement	380	121,79	8,53	26,60	0,4872	1,5200
Sika retarder (0,4%)	1,52	1,27	0,089	0,106	0,0051	0,0061
gravel	0	0,00	0,00	0,00	0,0000	0,0000
sand(≤2mm)	1720	649,06	45,43	120,40	2,5962	6,8800
water	228	228,00	15,96	15,96	0,9120	0,9120
		1000,12	70,01	162,96	4,0005	9,3120

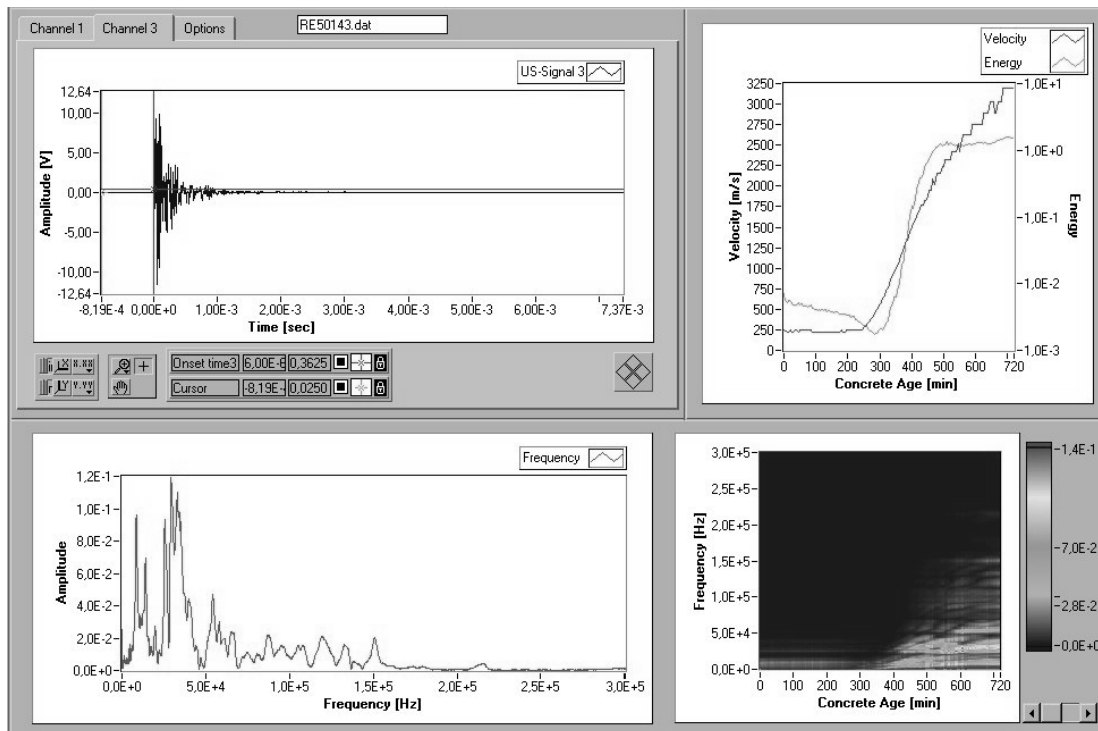


Fig. 1: Snapshot of the screen shown by the FreshCon2-Software after the US measurements at reference mix RE5 (see Tab. 1 and 2).

As described earlier [Ruck et al. 2001] the software developed at the University of Stuttgart called *FreshCon2* is able to do an online data analysis during the experiment in that way, that the operator has some control about test results. A screen-shot showing the software at the end of experiment RE5 is shown in Fig.1. Continuously the ultrasound signals with their Fourier transform (using an FFT algorithm) are recorded and plotted in the window at the upper left and lower left respectively. The shown graphs are representing the last transmitted signal and its frequency content – the whole experiment was

finished after 720 minutes (12 hours) and started approximately five minutes after adding water to the mix. As a recording interval five minutes was chosen as well to collect the data. In the upper right window the compressional wave velocity as well as the energy are plotted, calculated continuously using the onset time of the signal and the signal amplitudes respectively. Both parameters are changing significantly during the hardening of the material what is shown in more detail in Fig.2 for the presented data.

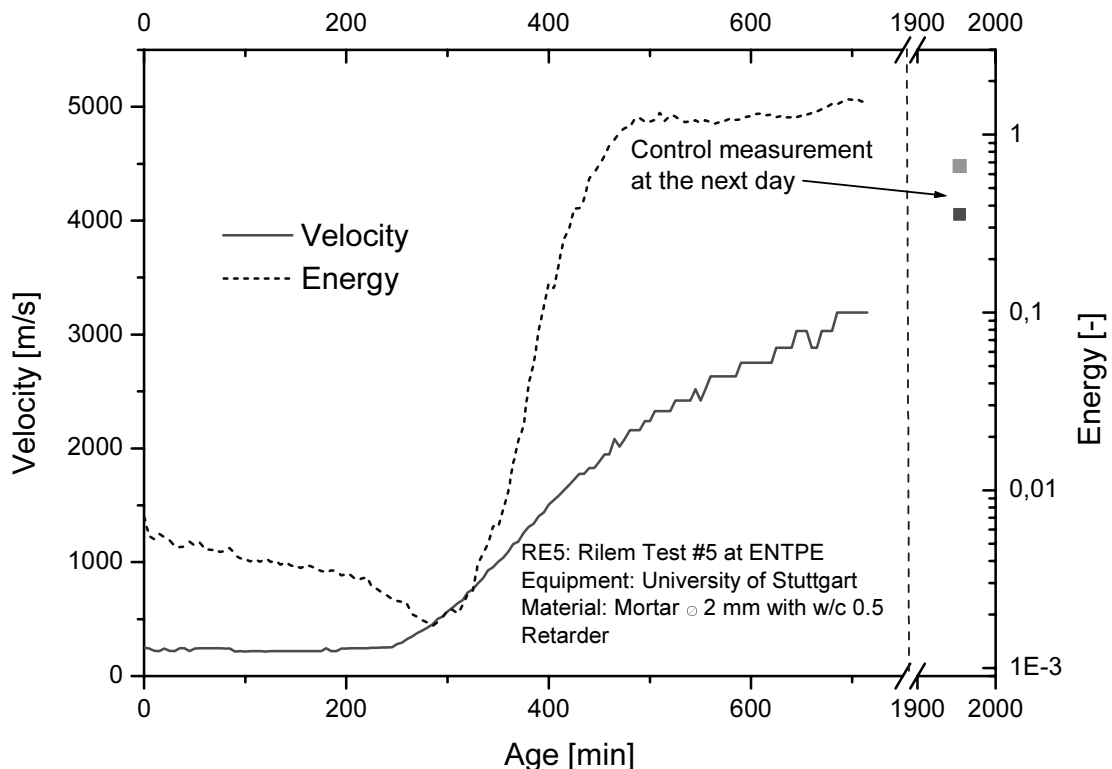


Fig. 2: Velocity and energy over the age of concrete (mix RE5).

The curves obtained out of the data by this device are characterizing the mixture to be tested. Concerning the velocities a 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. In the shown data from a mix with added retarder this increase occurs relatively late. To prove this, the velocities of the other experiments RE 1-6 listed in Tab.1 are compared in Fig.3. 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” in respect to hardening, while the RE5 mix with retarder is the “slowest” material. Further on, the mixes RE 3, 4 and 6 show a similar behavior due to the

compressional wave velocity. To distinguish between these materials more information contained in the signals has to be analyzed. This could be for example the analysis of the frequency content as shown in Fig.1 in the lower right or the wavelet analysis. On the other hand 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.

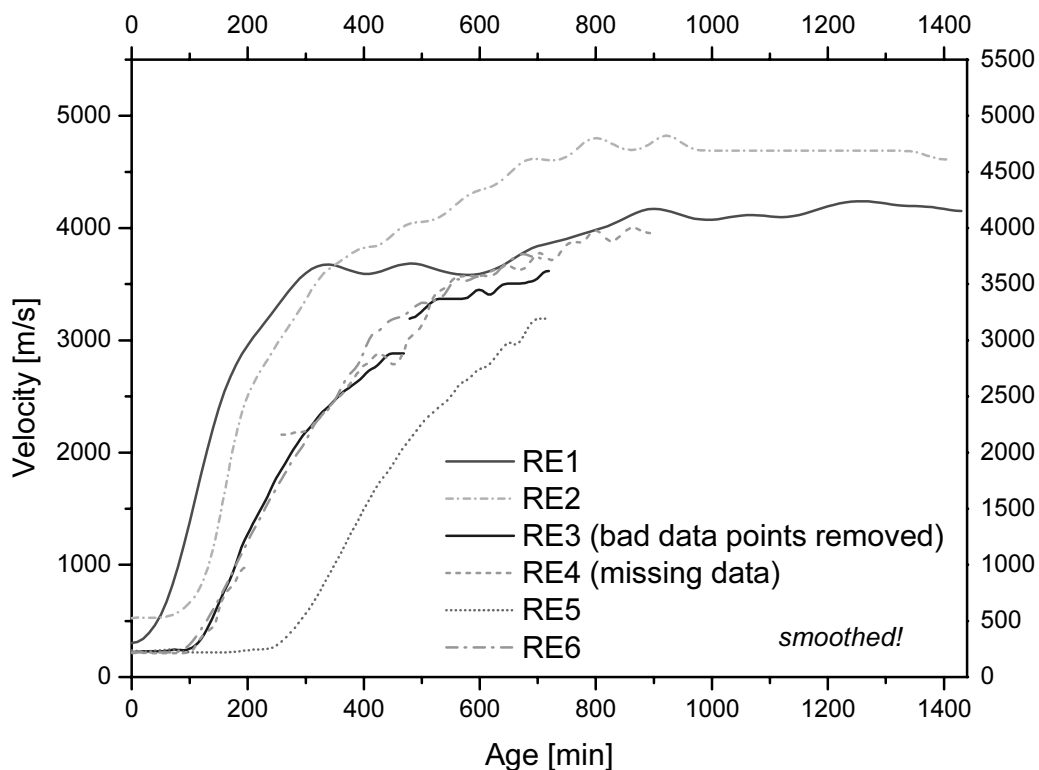


Fig. 3: Comparison of the velocity measurements testing mixtures RE 1-6.

Maturity methods and especially devices measuring the temperature depending on the age of the material are suitable to give more information. In an earlier research at the University of Stuttgart an adiabatic container was developed to extract temperature information from a cementitious probe [Köbele 1999]. During the round robin tests at the ENTPE the French group obtained temperature data with an own device using cylindrical probes. Fig.4 gives an impression of the temperature evolvment during the hardening of mixture RE 5. The temperature is rising in a similar way as the velocity after approximately 4 ½ hours (270 minutes) – there is a good correlation of both curves.

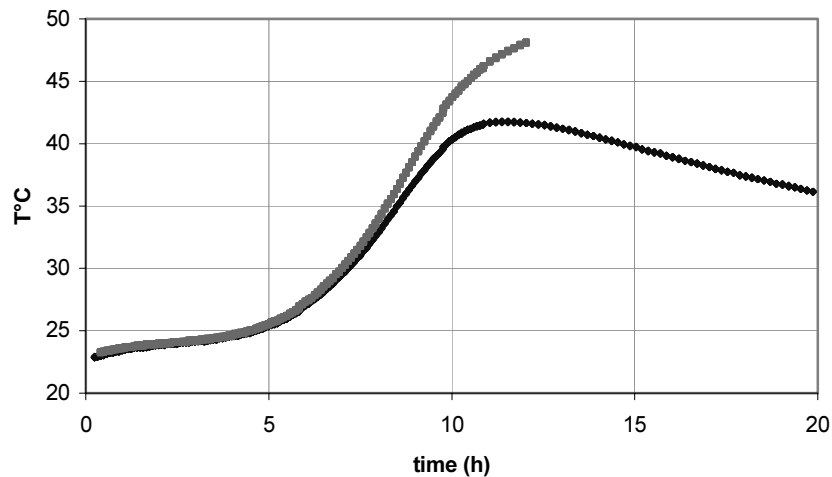


Fig. 4: Change of the temperature in the US specimen (upper curve) and in a probe of the same material filled in an adiabatic container (lower curve) during the experiment. (kindly given by ENTPE, Laboratoire Géomatériaux – Département Génie Civil et Bâtiment).

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. For example material parameters as water-to-cement-ratio, 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. 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.

Talking about the scientific aspects of the ultrasound technique, the method developed at the University of Stuttgart is under further progress. The degree of automatization is enhanced and additional analysis techniques will be implemented in future. In the frame of a diploma thesis [Manocchio 2001] the features of the wavelet transform (Fig.5) applied to the data were analyzed. There, the signal obtained in certain intervalls is transformed into the wavelet domain. Analyzing the signal in the time-frequency-domain enhances the information density drastically to correlate certain regions in the ultrasound signal with different frequencies contained in the wave.

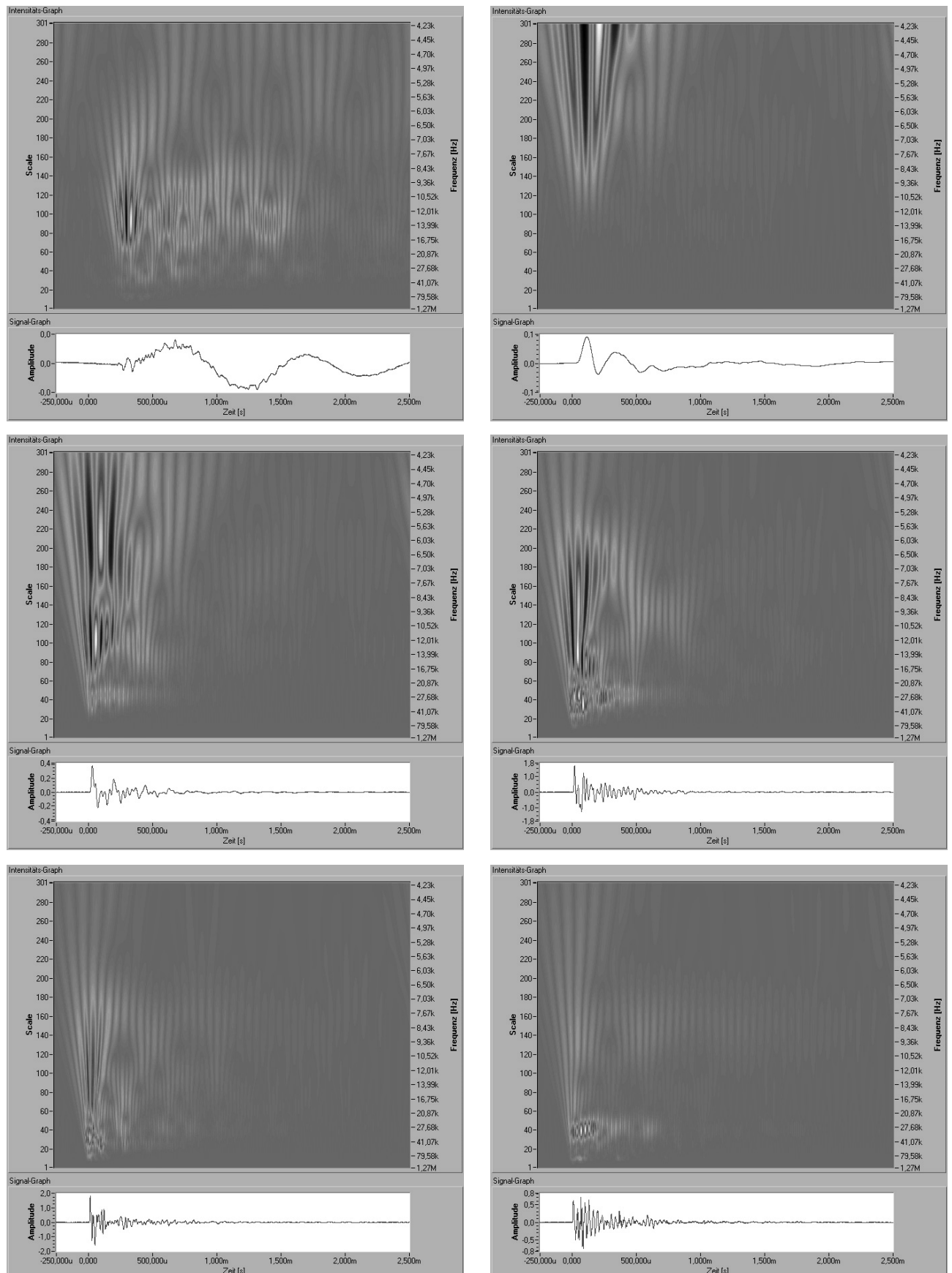


Fig.5: Example of wavelet-transforms of ultrasound signals obtained at six different ages (row wise from left to right and top to bottom: 50, 200, 330, 460, 600 and 1440 minutes) during the hardening of a concrete mixture. [Manocchio 2001; Beutel 1999]

Figure 5 gives an example of the changes of an ultrasound signal at six different ages (see caption). The transformed signal is plotted above as an intensity graph showing the scale (which can be seen as the frequency, see axis at the right) over the time of the signal, while the intensity is the wavelet parameter. While following the single graphs the change of the frequency characteristics depending on the age of the material becomes evident. In the first stage signals with low frequency content are dominant, while higher frequencies occur with increasing age of material.

At present the prospects to use this technique for a very detailed signal analysis are tested; results will be reported concerning different material mixtures as well as the discrimination of material effects against artifacts related to the transducer or the container.

With regard to the international activities of the RILEM technical committee more information can be obtained from the authors 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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