ULTRASOUND THROUGH-TRANSITION TECHNIQUES FOR QUALITY CONTROL OF FRESH CONCRETE

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Abstract
Ultrasound analysis techniques are applied based on the FreshCon equipment to investigate the setting and hardening behaviour of cementitious materials. The implemented data analysis techniques are applied using the whole waveform representing material properties. Parameters that could be extracted out of the signals are the velocity, the energy and the frequency content. Recently, the ability to record the temperature evolution over time was introduced as well as the determination of the associated hydration heat. For a rapid first interpretation of material properties the determination of the initial and final setting time was implemented. Comparing the graphs of different material compositions differences in quality as well as of the workability can be found easily.

The method can also be used to investigate the water-to-cement-ratio, the type of cement or the effect of additives as retarders or accelerators. Some application examples are the development of admixtures and the in-situ quality control during slip form concreting or precasting.

Keywords
Ultrasound analysis, FreshCon, setting behaviour, hardening behaviour, velocity, energy, frequency

1. INTRODUCTION
The methods currently employed by the construction industry for quality assurance of fresh concrete have already been practiced for many years and can be regarded as being established, although their measurement-technological possibilities are quite limited. Application of these methods is no longer in keeping with the possibilities offered by modern technology. Examples of these established methods are:

- Determination of initial and final setting of cement paste by Vicat-needle test (DIN EN 196-3)
− Consistence measurements by slump test (DIN EN 12350-5) or compaction test (DIN EN 12350-4) and in accordance with the slump test defined in DIN EN 12350-2, respectively
− Determination of air-void content by measurements as specified in DIN EN 12350-7.

An overview of the standards used in the past is contained in the literature [1]. The main disadvantage of most of the established methods is that they provide only a snapshot of the materials properties and that they cannot be used for investigating the continuous setting process. Reliable statements, e.g. on the mode of action of the admixtures for concrete can, as a rule, not be obtained with these methods.

On the basis of ultrasound techniques the properties of standard concrete and mortar mixtures can be measured – non-destructively, reproducible and largely objective. Of primary interest for quality control of fresh concrete is that the concrete parameters critically influencing the quality (e.g. the compressive strength) and workability (e.g. water-cement ratio, air-void contents), consistence, final strength, the effect of admixtures and many more, have a significant effect on the ultrasonic signal parameters, such as wave velocity, amplitude and frequency content. In particular the setting process of fresh concrete and fresh mortar can be investigated in detail. Accordingly, these methods are directly connected with the elastic properties of the materials, rather than with the chemical properties (as with the hydration or maturity measurement methods). By this method, individual measured values (speed, energy frequency) can be continuously recorded and represented during concrete aging, and the concrete parameters derived from these values (e.g. onset of setting, final setting) extracted.

Although the use of this technology is in general initially more costly (compared to the methods based on DIN EN 12350), the extra expense is compensated for by the more objective function mode, the improved reproducibility of the measured values and, last but not least, by a noticeable optimization of construction work flow. Areas of application for this method, where these advantages can be exploited are e.g. materials technology (development of new and more efficient concrete admixtures), in-situ quality control (sampling no longer necessary), slipform construction (optimization of stability) or precast concrete construction (optimization of work progress).

2. MEASUREMENT SYSTEM

2.1 Development of a reliable device

At the University of Stuttgart, an apparatus was developed aimed at investigating the setting and hardening of cement-based materials in quality assurance. First papers on this work were published in the early 90s [2]. The method was eventually patented [3]. A detailed description of the individual developments can be found in a publication by Grosse [4]. In recent years, the technology has attained a good industrial standard [5]. Proof of which, among others, is the fact that several research facilities and companies are by now successfully using the apparatus developed at the University of Stuttgart.

With regard to the apparatus technology, one of the focal tasks has been the development of an easily manageable container made of PMMA (Plexiglas, respectively) for carrying out the fresh concrete measurements, which was named FreshCon-1. In parallel to this, a separate measuring setup for mortar and cement paste was developed. Due to the clearly smaller aggregate diameter of typically less than 2 mm used, a much smaller container could be
developed. In this way, the sample size and consequently waste could be reduced to a minimum.

The construction of a U-shaped sample chamber (Figure 1) made of rubber was an important step towards industrial utilization. This development was apparently so attractive, also to other scientists, that it was copied – e.g. by a Korean group. Our new setup was named FreshCon-2 and FreshMor-2, resp., to distinguish it from older FreshCon systems. Another advantage of this concept is that here ultrasonic pulses could take place by broadband piezoelectric transmitter, obviating the need for a mechanical impact. This facilitates its application in practice.

![Figure 1: FreshCon container with sample holder out of rubber, PMMA walls and ultrasonic transducer and receiver](image1)

In essence, the two containers for mortar and concrete measurements differ only in their outer dimensions and in the test volume (concrete container: ten times larger volume) to enable the investigation of mixes with correspondingly larger aggregates (Fig. 2 [6]). With the aid of a piezoelectric transmitter, whose pulse energy is increased by a power amplifier, it is possible to produce signals that can be transmitted through fresh concrete – also using larger FreshCon-2 containers. This system has the advantage that mechanical parts are no longer needed (no impactor) so that in this way the reproducibility (in particular of signal amplitude measurements) is enhanced. In comparison to earlier devices also sensors were implemented with good linearity concerning the frequency response in the desired frequency range as well.

![Figure 2: Overview of the FreshCon-2 setup: power-amplifier (b), pre-amplifiers (e), container (d), broadband sensors (c) and computer (a) for data recording and analysis](image2)
as reliable power amplifiers on the transmitting and pre-amplifiers on the receiving side. The system has a good industrial standard and is in the meantime well used by several industrial and university partners.

3. MEASUREMENTS AND DATA ANALYSIS

3.1 Velocity and energy

One of the most important parameters for assessing the hardened state and other material parameters is the ultrasonic velocity, which can be derived from the travel time of the wave following transmission through the material. For velocity \( v \) applies in general the well-known equation \( v = s/t \) with travel time \( t \) and travel path \( s \).

![Figure 3: Example of the influence of different cements to the velocity development during setting and hardening of concrete](image)

When travel path \( s \) of the signal between transmitter and receiver (sensor) is known, the compressional wave velocity can be derived from the travel time of the signal. Measuring the transit times continuously and at fixed intervals, respectively, and deriving from this the velocity of the waves, one will obtain characteristic – often s-shaped – curves that image the hardening and setting. Comparable curves and materials compositions can be obtained for all hardened materials (e.g. mortar or concrete) as well as e.g. all types of admixtures. Figure 3 illustrates for example the effect of various cements, showing in this case the velocity in dependence on the concrete age. Fully automated determination of initial onset of the signal is of special significance to routine industrial application. With the system developed, this is performed with the aid of the WinPecker algorithm [7]; an improved algorithm invented by Kurz et al. [8] will replace this older approach. The software detects automatically the onset
of the signal and calculates the according travel-time as well as velocity of the signal. The time interval between the measurements can be set from seconds to minutes or even hours. Online the data can be displayed graphically.

In order to broaden the possibilities of interpretation, additional parameters of the ultrasonic signals can be made use of. Further information can be derived from the change in signal amplitude (and energy, respectively) (Fig. 4) and frequency content (Fig. 5) in addition to the velocity. Investigating the signal energy development during the entire hardening process is helpful. However, the high sensitivity of the energy in regard to the setting impedes the options for proper scaling of the y axis. The energy values in Fig. 4 in the first few hours are not zero but much lower than the values recorded after six hours. The high dynamic of energy values require sometimes even the use of logarithmic scales. The reliability and reproducibility of the measurement is high and was even improved using the newly designed FreshCon-2 system – an option for repetitive measurements was implemented averaging the signal over a very short period and eliminating incoherent noise. These techniques were implemented especially in regard to the energy evaluations requiring a robust and reproducible source. Prior hardware solutions provided not a sufficient technique for reliable energy investigations. As shown in Figure 5 the energy development can show sensitivity for different material effects compared to velocities. There are effects caused by changes of the status of the mix from a suspension to water saturated solids and some caused by air voids.

![Figure 4: Comparison of mechanical parameters (velocity and energy) with the hydration temperature of a mix](image)

**3.2 Frequency**

For frequency investigations, a form of Fourier transformation (FFT) is used, as in (Fig. 4), where the time signal can be seen on the top left and the frequency spectrum derived from it at bottom left. From the individual spectra, frequency graphs, e.g. waterfall or isoline graphs,
can be produced. Another example showing different behaviour of frequency isoline plots is presented in Figure 5. Further indications on the setting behaviour of the material can be derived on the basis of the time at which the individual frequencies in this isoline representation (contour plot) occur. All of these graphs characterize the material being quasi a fingerprint of the temporal hardening process.

Figure 5: Examples of frequency isoline plots obtained from mixes out of concrete and mortar, respectively

For application of the method in concrete practice, the correlation with established materials parameters is of interest. On the basis of automatic real-time determination of velocity and energy, a likewise automatic determination of initial setting and end of setting can be implemented for assessing the workability of the concrete [9] (Fig. 5). A comparison with the curves of standard mixes can then provide an overview of the materials behaviour and, e.g. the workability, of the mix. This carries the danger that, as a result of the compression of the complex graphs into individual parameters, a large portion of the information that has been gained from the time-dependent hardening process is lost.

Figure 6: Comparison of ambient (“air”) temperature with temperature in a Dewar container and in the specimen
3.3 Hydration temperatures

As the ambient and hydration temperature (in the FreshCon specimen and in the structural component) essentially influence the measurements, parallel measurement of these three temperatures is of advantage and can contribute on one hand to increasing the confidence and on the other giving additional information [10].

The FreshCon-2 software was for this reason extended accordingly and the hardware supplemented by a multiple-channel temperature data acquisition card. To obtain quasi-adiabatic data, a Dewar container was used additionally (Fig. 6). Here, account must be taken of the fact that the hydration process in the Dewar container, which simulates a thick structural component, takes place at a much faster rate and can therefore not be directly compared with a sample. This is also the reason why a comparison of these data with the ultrasonic measurements is problematic. The measurement of the hydration temperature during hardening anyhow describes more chemical changes. Figure 4 demonstrates this effect quantitatively in comparison to the velocity and energy evolution of the same material. Obviously the temperature developed much earlier than the energy of the transmitted compressional wave, while the wave velocity starts to increase at about the same time. One can assume therefore that the effect of the formation of ettringite needles is affecting more the wave propagation than the energy transport via elastic waves through the material. The wave finds its way through the skeleton of the hardening cementitious matrix while the dispersion is still high. A comparison with the change of elastic materials parameters is interesting and gives a more complete picture of the hardening process and therefore of the consistence and quality of the materials [11]. However, these things need still more investigations.

4. CLASSIFICATION OF THE RESULTS

Under certain circumstances the information obtained using the described methods is exceeding acceptable values and need for a reduction or condensation, respectively. As described earlier [12] the initial and final setting times of a mix is a parameter often used to classify the material in terms of workability. These values have been determined using more or less static parameters like the time when a certain velocity value threshold was crossed. More comprehensive techniques may be required and one is described in the following using the shape of the velocity curves only.

Figure 7: Sample curve demonstrating the influence of different parameters to the Boltzmann function (left) and the Logistic function (right)
This shape is usually like an “S” having different minimal and maximal values as well as different points of deflection and gradients. Therefore, the velocity data (for example obtained as shown in Fig. 3) can be fitted using the Boltzmann function known from thermodynamics:

\[ v(t) = \frac{v_1 - v_2}{1 + e^{(t-t_0)/dt}} + v_2 \]  

(1)

Figure 7 shows on the left side a sample Boltzmann curve indicating all relevant parameters in the above equation. \(v(t)\) is here the p-wave velocity (compressional wave), \(v_1\) is the initial and \(v_2\) the final velocity value. While \(t\) is the time related to the concrete or mortar age \(t_0\) is the center point between \(v_1\) and \(v_2\) of the curve and \(dt\) is a gradient. These values are specified in the sample curve. Looking at Figure 3 it is obvious that all shown data result in different \(v_1\), \(v_2\), \(t_0\) and \(dt\) values. These parameters can be used to describe the data [13]. One example is shown in Figure 8 for the “FreshCon_B03” data of Figure 3 along with typical statistical data.

Figure 8: Boltzmann functions fitted to two different data sets FBIE-3 and FBIE-6 from Fig. 3

It was found that typical data set obtained during setting and hardening show a slight deviation of the s-shape having a smaller branch in the beginning (early ages) with higher curvature. Fitting the Boltzmann function to these data results in unrealistic values for \(v_1\) and \(t_0\). This can be seen looking at the according values for the fit in Figure 8. Obviously, these data are better fitted using the “Logistic” function known from pharmacology, biology or chemistry as it is shown in Figure 7 on the right side. This function belongs to the sigmoid function group and is represented by:

\[ v(t) = \frac{v_1 - v_2}{1+(t / t_0)^p} + v_2 \]  

(2)
In this equation the function $p$ replaces the gradient $dt$. $p$ obeys the following constraint:

$$\left(\frac{t_1}{t_0}\right)^p = \frac{p-1}{p+1}$$

(3)

For “FreshCon_B06” data (Fig. 3) this fit function was applied showing much better correlations even in the initial setting period. A detailed analysis of best fitting functions and the influence of typical material parameters (type of cement, water to cement ratio, air content, admixtures) to fitting parameters is in progress. The suggested method for condensing ultrasound data using the Boltzmann function is not limited to velocity data. Similar functions can be used for fitting energy and even frequency data – provided that proper hardware can deliver reliable data showing mainly material effects and not artefacts.

5. APPLICATIONS AND OUTLOOK

Like applications in pattern recognition based on biometry the setting and hardening of cementitious materials can be analysed using ultrasound data. Moreover, the influence of all components of the mix can be analysed using comprehensive techniques based on the evaluation of velocity, energy, frequency and temperature measured during the setting and hardening. More sophisticated techniques can condense these comprehensive data. The suggested method for condensing ultrasound velocity data using the Boltzmann function is not limited to velocities. Similar functions can be used for fitting energy and even frequency data – provided that proper hardware can deliver reliable data showing mainly material effects and not artefacts. With the apparatus presented, a more efficient quality management of hardened materials in comparison to the methods currently in use is possible. Possible applications are in the field of materials development and optimization and for the development of new concrete admixtures, in-situ quality control on the construction site, for slipform construction or precast construction. The ultrasound method can, as a rule, be employed with little additional costs. Compact apparatus – as the one presented for evaluating concrete admixtures – work fully automatically and need very little maintenance; the requirements on the operating personnel are low. Other application of this technique deal with the investigation of shotcrete and fly ash cement as described in this proceedings and elsewhere [14]. Another method providing a one-side access method called impact-echo for similar purposes is also presented in these proceedings and elsewhere [15,16]. A comprehensive overview about these and other novel measurement techniques can be found in the book by Reinhardt and Grosse [17].

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