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Active and passive monitoring of the early hydration process in concrete using linear and nonlinear acoustics

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ABSTRACT

Microstructural changes occurring in freshly poured concrete during curing have been monitored on a laboratory scale using a combination of the Acoustic Emission (AE) Technique with linear and nonlinear ultrasonic/elastic wave spectroscopy. The AE technique is a passive ultrasonic signal recording technique capable of online monitoring the internal microstructural activity of young concrete during the hydration process. Ultrasonic wave spectroscopy is traditionally used to evaluate the material's longitudinal and shear wavespeed and attenuation properties (providing properties such as Young's Modulus of Elasticity, Poisson's Ratio and Quality factor) by means of an active excitation of a medium with pulsed sound waves. In addition to these traditional techniques, we have implemented a nonlinear version of ultrasonic wave spectroscopy which probes the nonlinear elastic properties of the microstructure (offering information about the micromechanical behaviour) through the analyses of the harmonic generation from a continuous wave transmission through the concrete sample. The evolution in the AE events, and in the linear and nonlinear ultrasonic behaviour of young concrete is analyzed as a function of the degree of hydration for various initial compositions during the first three days of the curing process. The results show a good correlation between the linear and nonlinear acoustic properties and the phase changes in the concrete due to chemical reactions and mechanical setting seen in the temperature profile.

1. Introduction

It is known that the durability of cement based products and concrete structures is highly influenced by the early stages of hydration. The creation of an interfacial transition zone between the aggregates and the cement paste, with a thickness of up to 50 μm, is considered to be the origin of primary defects in concrete leading to preferred paths for crack propagation and transport of aggressive agents threatening the durability of concrete. A precise knowledge of the micro-mechanical properties during the successive phases of the hydration process will provide information on the concrete resistance and allows assessment of its durability. Several non-destructive techniques have been developed and applied in that respect, most of them based on ultrasonic wave measurements. Keating et al. [1] observed a three stage evolution in the velocity of longitudinal waves in cement slurries after mixing. Many other researchers have observed similar patterns using ultrasonic pulse velocity measurements [2–14], and related these results, in combination with other physical parameters, to the hydration process. Boumiz [6,7] and Morin [11] used active ultrasonic echographic measurements providing the linear elastic material coefficients in combination with volumetric shrinkage measurements to describe the evolution of the capillary network of a High Performance Concrete during hardening. Feylessoufi et al. [12] determined a relation between the shear wave reflection coefficient and the percolation threshold of reactive powder concrete. Voigt et al. [13] investigated Portland cement mortar during hydration by means of the shear wave reflection method, and showed that the measurements are governed primarily by the degree of the inter-particle bonding of the cement particles as calculated from the specific contact area of a simulated microstructure. Passive energy recording using Acoustic Emission (AE) techniques has been used to evaluate the structural activity in concrete at early ages [14], showing periods of intense microstructural changes during the curing process. However, till now, the correlation between the linear elastic material properties, the number of AE-events and the micromechanical properties remains unclear, and a quantification of microstructural transformations (i.e. chemical and physical alterations and/or damage) induced by chemical reactions and setting during curing is not easily achieved.

The particular aspect of monitoring the influence of crack induced porosity on the micromechanics during hardening, may well be handled by nonlinear dynamic mechanical measurements. Nonlinear Elastic Wave Spectroscopy (or short NEWS) techniques represent a class of recently developed powerful tools which explore the dynamic

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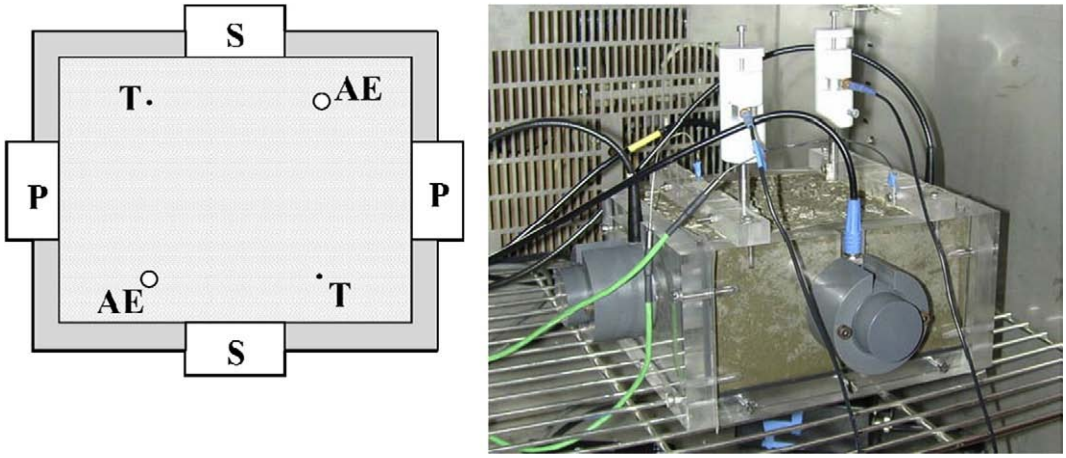

Fig. 1. Top view (left) and picture (right) of the curing cell used for monitoring the hardening process in young concrete. The monitoring devices include AE sensors (AE), thermocouples (T) and compressional (P) and shear (S) transducers.

nonlinear stress–strain features in the compliant bond system of a micro-inhomogeneous material and link them to micro-scale imperfections [15–21]. Micromechanical features such as hysteresis and elastic nonlinearity in the constitutive relation (at the micro-strain level) result in acoustic and ultrasonic wave distortion, which gives rise to changes in the resonance frequencies as a function of drive amplitude, generation of accompanying harmonics, nonlinear attenuation, and multiplication of waves of different frequencies [19]. In a series of laboratory NDT applications on various materials [15,18,20,21], NEWS techniques were found to be much more sensitive to mechanically and chemically induced structural alterations than any other method based on the investigation of linear material parameters such as wavespeed and damping.

In order to simultaneously probe the instantaneous microstructural activity and the micromechanical characteristics of freshly poured concrete during its curing process, we developed an integrated system of dynamic non-destructive techniques based on AE, linear ultrasonic wave propagation and NEWS harmonic monitoring. With this study, we complement and extend the work of Lacouture et al. [22] who started the use of NEWS for monitoring the first chemical reaction phase in the curing process. Here, we report NEWS results for the first three days of the hydration process. Using appropriate theoretical hydration models [23,24], we interpret these results within the framework of the degree of hydration concept. Eventually this work should lead to an improved prediction of the long-term behaviour of concrete and its performance dependence on the curing processes.

2. Setup for integrated passive and active monitoring experiments

2.1. Sample holder, instrumentation and concrete composition

The monitoring experiments were performed on a cubicle measuring 200 × 150 × 100 mm^3 (Fig. 1) during the first 72 h of the hydration process. The cell contains a circular opening on each of the sides to fit four transducer holders for the active ultrasonic measurements: a transmitter and receiver for both compressional (P) and shear (S) waves. The compressional transducers (Panametrics, 25 mm active diameter, 0.5 MHz central frequency) are positioned on the cross side and have a separation distance of 200 mm. The shear transducers (Panametrics, 25 mm active diameter, 0.25 MHz central frequency), placed on the long side, have a mutual distance of 150 mm. A thin film closing the apertures prohibits the freshly poured concrete from leaking through. Springs in the transducer holders ensure perfect contact between the transducers and the concrete. For the monitoring of the evolution of the inside temperature variation, two thermocouples are inserted from the (open) top side. Lastly, two very sensitive sensors (Vallen Systems, 20.5 mm diameter, 0.375 MHz central frequency) attached on top of two protruding bars register the Acoustic Emission (AE) signals emerging from the microstructural activity in the concrete sample.

We considered three different compositions of concrete, called DYNA 0.5 and DYNA 0.33, with a water/cement (W/C) ratio of 50% and 33% respectively, and SCC 0.5, a self compacting concrete with a 50% W/C ratio. Details of the compositions are presented in Table 1.

2.2. Integrated monitoring procedure

The monitoring measurements are performed in a temperature controlled room. After pouring the fresh concrete in the cubicle, the instrumented sample is placed in a climate chamber (Heraeus-Vötsch Climate Cabinet VLK 04/150) (Fig. 2) to isolate it from large outside temperature and relative humidity fluctuations. The climate chamber is closed. However, climate conditions are not actively controlled in order to allow and to monitor the variations of the concrete's inside temperature, which are characteristic for the concrete curing process. The (damped) temperature inside the climate chamber is also registered and is used to correct the thermal fluctuations in the concrete sample for day–night cycles.

Fig. 3 depicts the instrumentation scheme of the experimental setup, which consists of two computer controlled systems. One system (Digital Wave) is registering the AE events, the second one performs the ultrasonic measurements (both linear and nonlinear) and the temperature reading. Both systems are independent from each other, except for the communication about the interruption of the registration at certain times. A LabVIEW script controls the acoustic measurements, adjusting the function generator (Agilent 33250A) and the oscilloscope (LeCroy 9310AM) settings through GPIB-IEEE488, and monitors the acoustic responses. Temperature (3 readings: inside temperatures $T_{in,1}$ and $T_{in,2}$, and outside temperature T_{out}) and relative humidity (RH) are logged on the same PC.

Table 1
Compositions of concrete (all units are in kg/m^3, except when mentioned otherwise).

	DYNA 0.5	DYNA 0.33	SCC 0.5
Sand (0/4)	670	625	696
Aggregates (4/14)	1280	1190	875
Water	150	150	175
CEM I 42,5 R	300	450	350
Plastifier Rheobuild 2000 PF (cc)	1500	4500	1200
Filler 2001 MS (cc)	–	–	276