MONITORING OF FRESH CONCRETE CURING BY COMBINED NDT TECHNIQUES

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Abstract

Ensuring the quality of fresh concrete and suitable curing conditions substantially reduces the possibility of future failure to perform as designed. However, the most reliable examination for concrete is mechanical testing after hardening. In order to obtain better control on the process from very early age, this study describes a combined approach of several monitoring techniques. Acoustic emission is used to record the numerous events occurring during the first hours when concrete is in liquid form as well as later when hardening takes place and drying shrinkage cracking is exhibited. In addition, pressure sensors follow the development of capillary pressure in the matrix and indicate the moment of air entry into the system. Settlement and shrinkage, measured both non-contact by digital image correlation and conventionally, as well as temperature shed light into the complex processes occurring into fresh concrete and help to verify the sources of AE. The final aim is to develop a methodology to assess the quality of the fresh concrete from an early age, to possibly project to the final mechanical properties and to ensure a proper service life.

1. INTRODUCTION

Monitoring of the early stage of the material is important as this stage defines the final properties of the hardened concrete. Acoustic emission (AE) has been increasingly used as it shows sensitivity to wave signals during the setting of the material and as early as from the moment of mixing. Many processes occur like settlement, formation of bubbles and hydrates, mobility of aggregates, bubbles and water and shrinkage cracking, among others. Since all of them may overlap in time, it is in general a very difficult task to explain the origin of AE populations. This paper wishes to contribute in the field by isolating and examining two physical mechanisms, namely impact of aggregates due to settlement/segregation and bubble release. Experiments are conducted by impacting aggregates in paste in a controlled way as well as creating bubbles by inducing air pressure in cement paste through a hose, while the process is monitored by acoustic emission (AE) sensors. The AE technique detects stress waves emitted by irreversible processes within a material. These processes may be damage propagation of any form, other specific processes, like leakage from a pipe or activities occurring in fresh concrete. In a general case, piezoelectric transducers are applied on the surface of the material to transform pressure changes on their surface in electric waveforms. These signals are amplified and led to the acquisition board where they are stored in a digital form [1,2]. A representation of an AE setup tuned to the current application is given in Fig. 1.

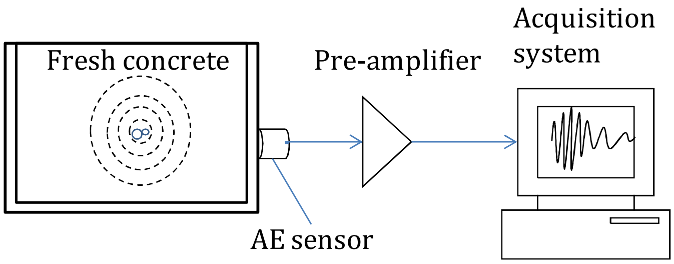

Figure 1: Typical AE setup

The basic parameters of a recorded waveform are the amplitude, the duration, the energy (area under the rectified envelope), the frequency content measured by the threshold crossings over the duration and others [1,2].

In the field of fresh concrete there have been a few studies dealing with AE monitoring dealing with the setting and the hardening stage [3-9]. The contribution of all above mentioned studies is important in that different mechanisms are targeted. It is shown that if the setup allows, numerous AEs are monitored even from the moment of mixture, before the hydration reaction essentially starts. In this study two such mechanisms are investigated in terms of their AE production potential, namely the aggregate impacts and air bubble release.
Recently, in an effort to combine different techniques, two AE sensors were attached on the outer side of standard steel moulds 40x40x160 mm, containing fresh paste and mortar. Ultrasound pulse velocity was also monitored as well as capillary pressure in a different mould of the same batch. Results showed very high AE activity from the moment of mixing which gradually came to a saturation after approximately 3-4 hours. This was followed by a period of negligible activity and then some moderate activity was again noticed (Fig. 2). The development of settlement measured by a displacement sensor at the top surface (LVDT), showed very similar trend, implying that processes related to settlement (bleeding, segregation, packing of the cement grains) are responsible for the early age AE [10].

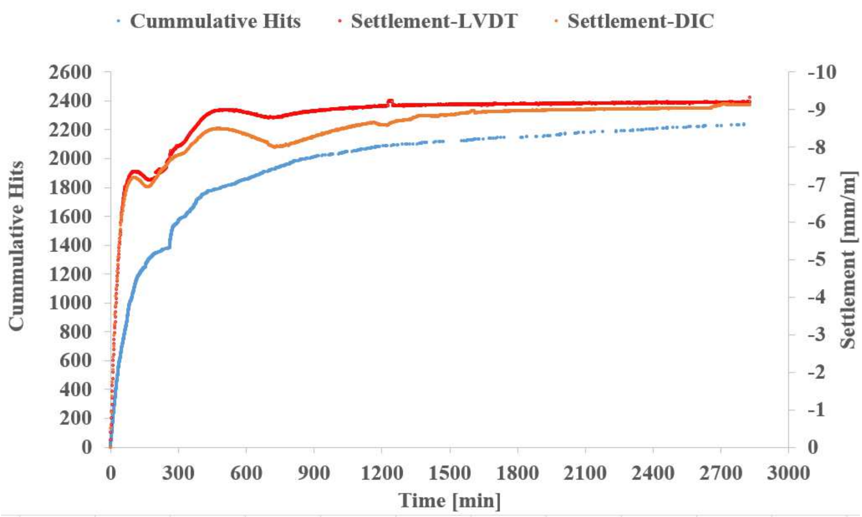

Figure 2: Cumulative hits and settlement versus time.

2. EXPERIMENTAL SETUP

The AE system of this study is a Micro-II express of Mistras Group that allows recording of the full AE waveform. AE monitoring was applied by means of three piezoelectric sensors (R15, resonant at 150 kHz, Mistras). They were attached on the outer side of the steel mould with the shape of 40x40x200 mm (internal dimensions) and thickness of 10 mm. To enhance the coupling between the mould surface and the sensors, a viscous silicon grease was applied on the surface of the sensors. More details on the experimental setup can be seen in [11]. Figure 3a presents a photograph of the experimental setup. The vertical distance between the sensors on the steel mould is 50 mm. For the experiment with aggregate impacts, different sizes of glass spheres were used, namely 3, 5 and 8 mm to study the impact in air (empty mould), water and fresh cement paste. The glass spheres were let to drop from the top to the bottom of the mould to monitor the impact on AE by the three sensors. Furthermore, concerning the air bubble investigation a nozzle was arranged vertically at different heights in the same steel mould. The nozzle allowed air into the mould, containing either water or fresh cement paste, see figure 3b. The pressure was set to the minimum as the intention was to have a slightest possible bubble creation with the indication being 0 bar in the meter). The measurement (glass ball drop or introduction of air pressure) started immediately after casting the cement paste into the mould. The duration of the AE experiments was between 5 and 8 min in order not to allow any change of the texture due to possible hydration [11].

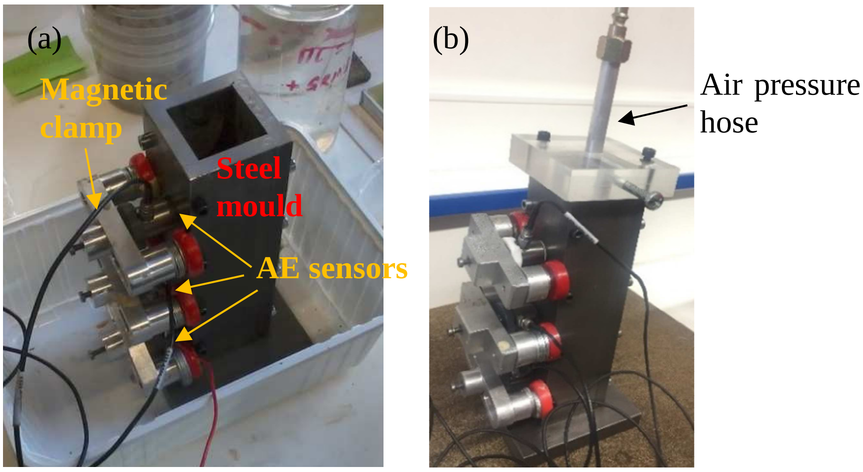

Figure 3: (a) Photograph of the experimental setup, (b) photograph of the experimental setup for air pressure application.

3. RESULTS

3.1 Aggregate impacts

Each time a sphere was let to drop in an empty mould (reference), it bounced several times, which could be easily measured by the corresponding AE signals. Specifically, each drop was accompanied by three hits (one received by each sensor). The sensor at the bottom (ch.8), which was closer to the impact point, registered each time the highest amount of energy. After the sphere bounced on the bottom surface another sequence of three hits was recorded by all sensors and with the same order in energies and delay times related to the position of the sensors. In Fig. 4a one can see the energy of the successive signals and even measure how many times the sphere bounced on the bottom.

The corresponding results from a similar test in a water-filled mould are shown in Fig. 4b. In this case, the energy of the first hits is one order of magnitude lower (10^7 attoJ), the delay between successive bounces is much longer and only three bounces are evident. This difference can be attributed to the effect of friction and water viscosity that does not allow transformation of the whole dynamic energy to kinetic during the drop of the sphere, essentially slowing down the sphere.

Finally, Fig. 4c presents the AE energy registered by the three sensors in the presence of fresh cement paste. In this case the viscosity and density of the cementitious matrix is much higher than water and this does not allow any bounce after the initial impact while the energy level is much lower. These results come from individual representative drops of a sphere of 3 mm. Numerous drops have been conducted and averaging results are discussed later in the text.

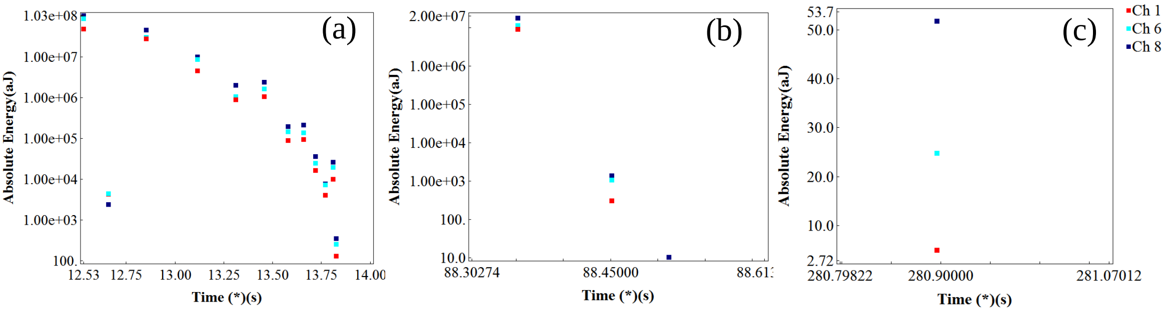

Figure 4: Absolute AE energy for impact of glass sphere in (a) empty mould, (b) water-filled mould, (c) paste-filled mould.

Fig. 5 shows actual waveforms as received by the three AE sensors in (a) empty mould, (b) filled with cement paste for all three sensors. The waveforms come from the first impact of the sphere. The propagation conditions are very complicated, but is seen that, especially in the third top sensor (ch.1, further away from the impact) some initial weak arrivals precede the higher amplitude burst coming some tens of μs later. This is typical for plate wave dispersion and it is the possible reason for this observation, as considering the frequency of the waves (approximately 150 kHz), the wavelength is calculated at around 30 mm, much longer than the thickness of the mould wall of 10 mm. For the case of cement matrix, as seen in Fig. 5b, the waves are of much smaller amplitude, less than 1% of the water and air waveforms, but they carry higher frequencies.

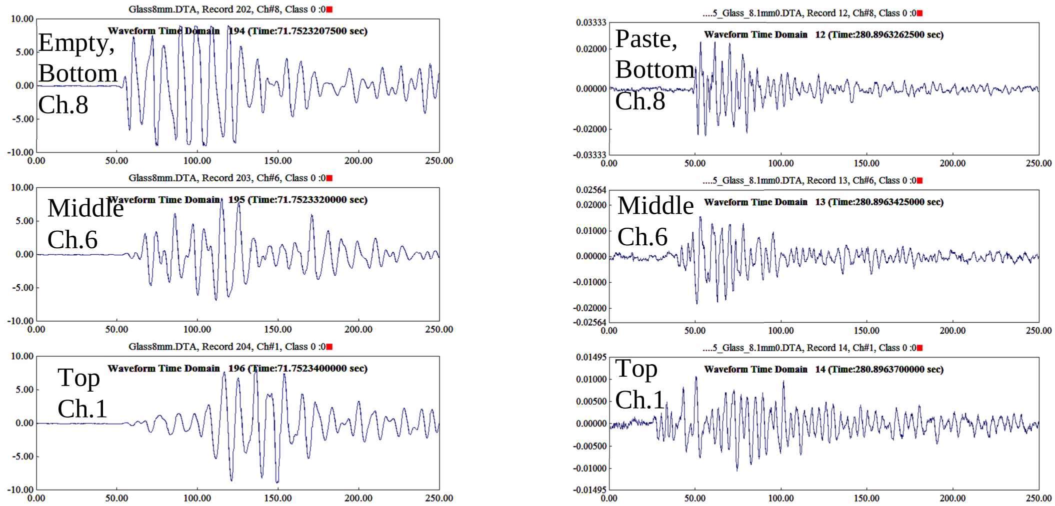

Figure 5: AE Waveforms of the three sensors after a single impact in (1st column) empty mould, (2nd column) paste-filled mould.

Indeed, as seen in Table 1 the initiation frequency (counts to maximum/time to maximum) for the first case is 120 kHz, while for water filled and paste filled mould the frequencies average on 162 kHz and 778 kHz respectively. This difference is quite important bearing in mind that the same sensors are used in all cases. This may seem contradictive with the increasing viscosity, but it should be considered that nearly the whole amount of acoustic energy propagates through the metal wall and not the liquid medium. The duration and rise time indicators are in the inverse order than frequency, with impacts in empty mould exhibiting 30 times longer waveforms than paste-filled. A reasonable explanation is related to the contact time between the sphere and the bottom surface of the mould. This time is inversely proportional to the excited frequencies after impact [12]. The contact time is expected much shorter in the case of paste-filled mould since the speed of the sphere at impact is low.

Table 1. Average values of AE parameters for 3 mm glass sphere impacts

Filling of mould	Duration (μs)	Risetime (μs)	Amplitude (dB)	AF (kHz)	Initiation Frequency (kHz)
Empty (air)	10500	178	98.2	95.7	120
Water	3680	140	97.7	251	162
Paste	33.7	1.67	44.7	117	778

The general conclusion from the above results is that aggregate impacts (due to settlement or segregation) are a mechanism that can certainly be monitored by AE sensors attached on the mould.

3.2 Effect of bubble release in water

In this type of experiment, after establishing a certain minimum pressure in the pipe, a steady state was accomplished in the specimen; regular AEs were recorded, and visible bubbles were seen on the surface of water or paste, when the nozzle was placed close to the middle of the height of the mould. Figs. 6 (a) and (b) show the amplitude of AE according to the different channels for bubble creation in water and in cement paste. Though the range of values of amplitude does not seem to differ much, a certain observation is that bubbles in paste create a much higher number of AEs. While for water the AE rate is about 1 hit/s, for paste it is nearly 30 times higher.

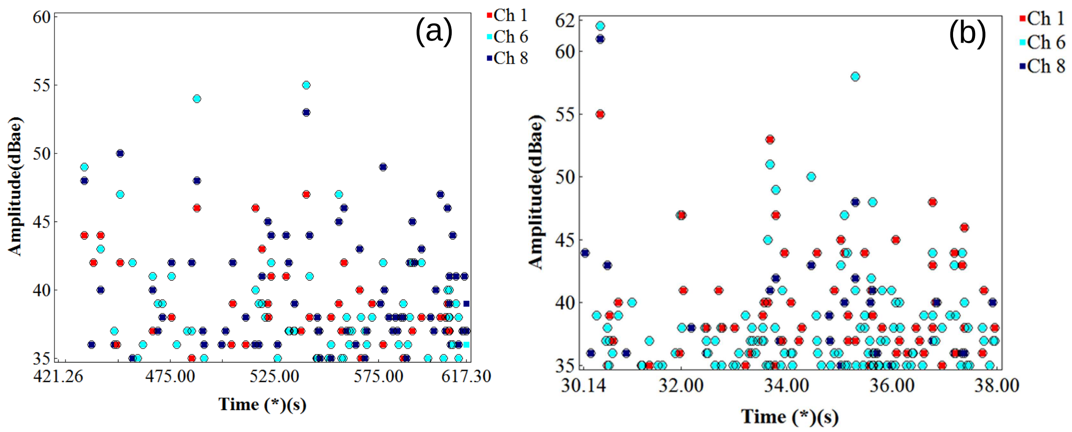

Figure 6: AE parameters for bubbles release in different media: (a) amplitude in water, (b) amplitude in paste.

Table 2 shows the basic parameters of AE for bubbles released in water and paste. AE waveforms in paste have much shorter duration in average. Correspondingly they also have shorter rise time. One reasonable explanation is the damping of paste which would quickly attenuate the later cycles of the signal. In this case the bubble is created within the paste matrix and not in contact with the mould. Therefore, the viscosity of the matrix plays a more important role as there is no other way for wave energy but to propagate through paste. Even though the experiment was done with resonant sensors, the AF and IF again present consistent differences. The AE through paste again shows higher frequency measures (AF and IF).

Table 2. Average values of AE parameters for bubbles in different liquid matrices.

Filling of mould	Duration (μs)	Risetime (μs)	Amplitude (dB)	AF (kHz)	Initiation Frequency (kHz)
Water	236.5	48.2	39.3	138.9	359.8
Paste	42.1	8.1	38.6	222.5	565.8

The waveforms of Fig. 7 indicate that AE waveforms through water exhibit longer duration characteristics. However, it is possible that one bubble creates more AE signals while it rises to the surface, e.g. by "friction" with the mould or the air pressure pipe.

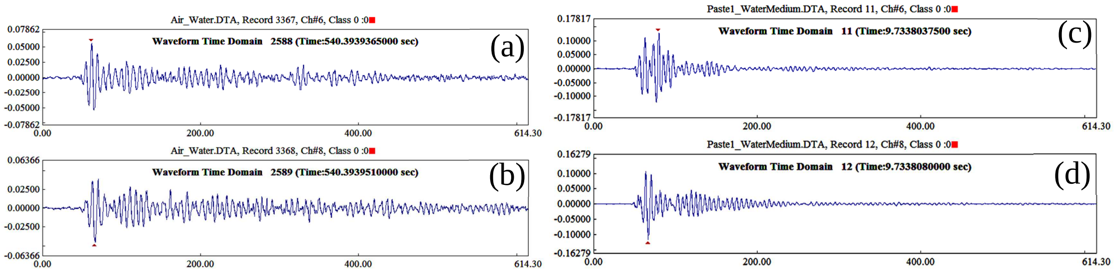

Figure 7: Successive typical AE waveforms during bubble creation, (a and b) water-filled mould, (c and d) paste-filled mould.

In the above experimental results, it is evident that both mechanisms of aggregate impact, as well as bubble creation and movement produce recordable AE within a fresh cement specimen. The aggregate impact seems much more intensive mainly because of the direct contact to the mould. Numerical simulations are desirable to enlighten the wave propagation conditions of the experiment [11].

4. CONCLUSIONS

Two physical processes occurring in fresh cement-based materials are targeted as to their potential to create AE as well as the possibility to be characterized through it. The basic conclusions can be summarized as follows:

- Movement of aggregates due to settlement and segregation as well as creation and movement of bubbles through the liquid matrix constitute detectable AE sources.
- Processes that occur close to the container mould wall are received by the sensors with higher amplitude indicating that placing sensors on the mould is a suitable experimental strategy.
- Although the liquid matrix supports only a small amount of the acoustic energy, it exercises a certain effect on the received wave indirectly as it controls the mobility (e.g. physical speed) of the constituents (e.g. aggregates and bubbles).

This study is the preliminary investigation of the effect of physical mechanisms occurring in fresh concrete. The study will go on with continuous monitoring to check how the mechanisms behave with time and to include other mechanisms that can be of physical (cement grain settlement, early age cracking) or chemical character (formation of hydrates).

ACKNOWLEDGEMENTS

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REFERENCES

[1] Grosse, C.U., Ohtsu, M.: Acoustic Emission Testing. Springer, Berlin (2008)
[2] Mix P.E., Introduction to Nondestructive Testing, A Training Guide, John Wiley & Sons, Inc.,

Hoboken, New Jersey

[3] K. Van Den Abeele, W. Desadeleer, G. De Schutter, M. Wevers, Active and passive monitoring of the early hydration process in concrete using linear and nonlinear acoustics, Cement and Concrete Research 39 (2009) 426–432

[4] V. R. Skal’s’kyi, P. M. Koval’, O. M. Serhienko, and Yu. L. Lotots’kyi, Investigation of the solidification of concrete according to the signals of acoustic emission, Materials Science, Vol. 40, No. 5, (2004) 698-701.

[5] P. Lura, J. Couch, O. Mejlhede Jensen, J. Weiss, Early-age acoustic emission measurements in hydrating cement paste: Evidence for cavitation during solidification due to self-desiccation, Cement and Concrete Research 39 (2009) 861–867.

[6] V. V. Bardakov, A. I. Sagaidak, Forecasting of concrete strength during the hardening process by means of Acoustic Emission method, PROGRESS in ACOUSTIC EMISSION XVIII, Proceedings of the 23rd International Acoustic Emission Symposium, the Inauguration Conference of International Institute of Innovative Acoustic Emission & the 8th International Conference on Acoustic Emission JSNDI & IIIAE, 2016, Editors T.Shiotani, S.Wakayama, M.Enoki, S.Yuyama

[7] Lei Qin, Hong-Wei Ren, Bi-Qin Dong, and Feng Xing, Acoustic Emission Behavior of Early Age Concrete Monitored by Embedded Sensors. Materials 2014, 7, 6908-6918; doi:10.3390/ma7106908

[8] L. Topolár, L. Pazdera, B. Kucharczyková, J. Smutný and K. Mikulášek, Using Acoustic Emission Methods to Monitor Cement Composites during Setting and Hardening, Appl. Sci. 2017, 7(5), 451; doi:10.3390/app7050451

[9] M. Ohtsu, Chapter 5: Acoustic emission in concrete of early-age, H.-W. Reinhardt, C. Grosse (Eds.): Advanced testing of cement-based materials during setting and hardening. RILEM Report 31, ISBN: 2912143705, RILEM Publ. S.A.R.L.: Cachan ENS, 2005, ca. 341 p.

[10] E. Dzaye, G. De Schutter, D. G. Aggelis, Early-age monitoring of fresh cementitious material by acoustic emission, p. 417-422. In the Proceedings of the 2nd International RILEM/COST Conference on Early Age Cracking and Serviceability in Cement-based Materials and Structures, PRO 120, RILEM Publications S.A.R.L.

[11] Evin Dildar Dzaye, Geert De Schutter, Dimitrios G. Aggelis, Study on mechanical acoustic emission sources in fresh concrete, Archives of Civil and Mechanical Engineering, 18(3) 2018, 742-754.

[12] M. Ohtsu, M. Yamada, T. Sonoda, Quantitative evaluation of SIBIE procedure and case studies, Construction and Building Materials, 48, 2013, 1248-1254