# Monitoring of fresh concrete exposed to various environmental conditions using Acoustic Emission (AE) and Digital Image Correlation (DIC)

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## ABSTRACT

Early-age concrete undergoes displacements and volume changes due to ongoing processes such as settlement, hydration, shrinkage, and cracking, which can strongly affect its durability and long-term performance. In this paper, fresh concrete is monitored by the non-destructive techniques of Acoustic Emission (AE) and Digital Image Correlation (DIC). Elastic waves released by the physical processes taking place while concrete is in a fresh state can be well-recorded by AE, while the three-dimensional strain and displacement evolution on the surface can be measured by DIC. Monitoring fresh concrete is of paramount importance to ensure the desired final mechanical properties, especially when novel admixtures for internal curing such as SuperAbsorbent Polymers (SAPs) are added to the mixture. SAPs are particles that can swell by absorbing water when exposed to it, and later release it back to the cementitious matrix when the internal relative humidity linked to the capillary pressure decreases, mitigating autogenous shrinkage. These admixtures strongly interact with the microstructure, resulting in an increased amount of AE activity. The motivation of this study is to obtain real-time information on the different ongoing processes in fresh concrete using AE and compare the results to concrete containing SAPs. Specimens are subjected to different environmental conditions, to monitor the changes in the SAP activity. Results are complemented by DIC to confirm the mitigation of shrinkage by the SAPs. The DIC results showed that SAPs mitigate settlement and shrinkage in early-age concrete, while AE showed SAP concrete exposed to windy conditions demonstrated a delay in the SAP activation, lower amplitude values and higher peak frequency values than the ambient SAP concrete.

**Keywords:** Acoustic emission, concrete, digital image correlation, shrinkage, superabsorbent polymers

## 1. INTRODUCTION

Fresh cementitious media are characterized by complex processes from the moment of mixing throughout their curing period. The physical and chemical phenomena taking place during the early stages of fresh concrete are closely related to the final mechanical properties. Therefore, monitoring the early-age processes can provide important information about concrete curing and its influence on long-term performance. Acoustic Emission (AE) is a non-invasive technique that presents high sensitivity in recording elastic waves released by irreversible processes within the material. Non-destructive techniques like AE have been utilized by researchers often in the last years to monitor the behavior of fresh cementitious media [1-3]. AE can collect real-time data and it can be used to characterize and distinguish the various processes taking place in the fresh material. Previous studies performed on fresh concrete showed that most of the AE activity during the first 2 hours after mixing comes from the settlement, while AE energy exhibits peaks close to the moment of capillary pressure breakdown indicating the risk of plastic cracking [4].

In fresh cement-based materials, the volume changes due to the hydration and stiffening processes can lead to early-age shrinkage. Other factors that can affect shrinkage evolution are moisture loss, thermal deformations, and hardening due to changes in pore water content.

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SAPs are particles that can swell by absorbing water when exposed to it, and later release it back to the cementitious matrix when the free water is exhausted, promoting autogenous healing [5]. Literature has shown that the SAP action is accompanied by high bursts of AE data [6]. The SAP action has a specific duration after its onset. More specifically, some types of SAPs tend to provide the entrained water all at once under harsh conditions. The reaction of SAP to different environmental conditions is essential to characterize their behavior.

The surface mobility of fresh concrete due to shrinkage and settlement can be monitored by Digital Image Correlation (DIC), a contactless technique that can be used to create a three-dimensional map of the strains and displacements. DIC can be used to interpret the surface mobility of fresh concrete due to shrinkage and settlement. This method can be very useful to validate the shrinkage mitigation by the SAPs. Two digital cameras are perpendicularly facing the specimen's surface and are stereo-calibrated to a certain position. Then a sequence of pictures is taken, which will later be compared to the reference image. This way, displacements, and strains can be tracked. A black-white speckle pattern is created on the surface of the specimen which deforms along with the material, allowing monitoring displacements just a few minutes after casting. Literature has shown that DIC can be successfully applied on fresh concrete, even though the application of the speckle pattern is a challenge due to the surfacing of the bleeding water immediately after casting [7].

For this paper, AE was applied on concrete cubes in combination with DIC, to monitor the behavior of fresh reference concrete and concrete containing SAPs. The motivation is to compare real-time information on the different ongoing processes in fresh concrete. In the first series of experiments, reference concrete and concrete containing SAPs were monitored by AE and DIC to validate the shrinkage mitigation by the SAPs. In a second series of experiments, SAP concrete is subjected to different environmental conditions (ambient and windy conditions), and AE was used to collect real-time data on the changes in the SAP activity. The DIC results showed that SAPs mitigate settlement and shrinkage in early-age concrete, while AE showed that specimens exposed to wind demonstrated a delay in the SAP activation.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The two compositions investigated in this study were a reference mixture, and a mixture containing SuperAbsorbent Polymers (SAPs). The reference composition, here named REF was made with Portland cement (CEM I 52.5 N Strong, Holcim, Belgium), and a water-to-cement ratio of 0.35. Coarse gravel stones, fine stones (sizes 6.3/14 mm and 4/8 mm, respectively) and river sand (0/2 mm) were added in a proportion of 2.36:1.27:1.27 with respect to cement weight. The solid components were dried in the oven for 48 hours and were then let to cool down naturally, at room temperature, before mixing. To ensure sufficient workability, superplasticizer (Glenium 51, conc. 35%, BASF) was added to the mix at a percentage of 0.6% by cement weight.

A second composition here named SAP was investigated which contained 0.2% SAPs per cement weight. The SAP composition had the same amount of aggregates, cement, sand and superplasticizer as the reference. The utilized SAPs were a bulk-polymerized, cross-linked copolymer of acrylamide and acrylate, with a particle size < 600 μm and were provided by Floerger SNF. This type of SAPs has a swelling capacity of 262.21 ± 5.45 g/g SAP in demineralized water and 21.15 ± 1.60 g/g SAP in cement filtrate solution [8]. The particular SAPs were used in this study as an agent to stimulate autogenous healing. An extra amount of water, equal to 30 grams per gram of SAPs was added to the mix to obtain an identical flow as the reference mix. Both mixtures showed the same workability. For the SAP composition, a second series of specimens was studied, which was exposed to windy conditions, using a table-electric fan during the whole monitoring period. The fan was operating at a moderate air speed of 44 m/s. These specimens are named SAP_F.

### 2.2 Specimens

The mixture was prepared at a laboratory concrete mixer, where the material was mixed at 361 RPM. The total mixing time was four minutes – one minute of dry mixing, followed by three minutes of mixing with water. Then the material was poured into a 150x150 mm (internal dimensions) metallic mold. The mix was poured into two layers and was vibrated for 20 seconds between each layer, at a high frequency. The surface was then smoothened using a bucket trowel so that it is prepared for the DIC measurements. After, the whole surface is painted white and fine black speckles are sprayed on top, to create the speckle pattern for the DIC monitoring. Each specimen was monitored for approximately three days and then sealed and cured at ambient conditions (T = 20±1 °C, RH = 50-60%) for 28 days before being subjected to compression tests.

## 2.3 Methods

Five R15a piezoelectric sensors of a 150 kHz resonance frequency were used to monitor the AE activity, while the acquisition was performed by Micro-II express acquisition system by Mistras Group. The sensors were placed at every outer side of the mold, at different heights, using magnetic clamps and a coupling agent. A threshold of 35 dB was set to filter out environmental noises. The signal was amplified by 1220A preamplifiers of 40 dB. The coupling efficiency of the sensor to the mold was ensured by performing pencil lead breaks close to every sensor before the initiation of the monitoring, as well as at the end.

The surface displacements and strains were tracked in three dimensions using the DIC technique. Two digital cameras were placed 300 mm above the specimens' surface. The cameras are stereo-calibrated to a certain position, and then a sequence of pictures is taken, which will later be compared to the reference first image. The reference image is taken 10-14 minutes after water is added to the dry materials. This way, displacements, and strains can be detected. A speckle pattern is created on the surface of the specimen which deforms along with the material, allowing monitoring displacements just after a few minutes after casting. The speckle pattern was created by spraying black and white paint on the surface of the specimens. VIC-Snap and VIC-3D software were used for the DIC measurements and post-processing, respectively.

For the SAP_F specimens, a normal fan was placed in front, to investigate the influence of windy conditions on the SAP behavior. All measurements started approximately 10-14 minutes after water was added to the dry material. The measurements were performed at ambient conditions (T = 20±1 °C, RH = 50-60%). A schematic view of the experimental setup can be found in Figure 1.

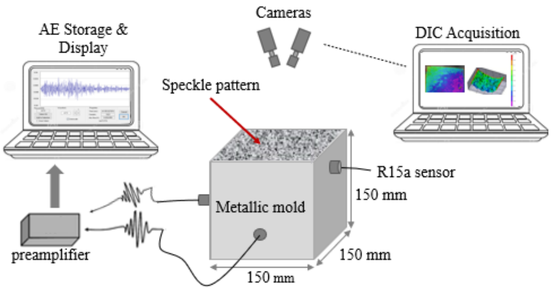


Figure 1. Schematic view of the experimental setup.

# 3. RESULTS AND DISCUSSION

## 3.1 Early-age internal processes in concrete by AE

Figure 2 shows the cumulative AE activity of the indicative monitored specimens. The SAP cubes show a significantly higher cumulative activity compared to the REF cubes (Figure 2-left). The increased activity is attributed to the SAP action. SAPs are activated around 14.5 hours and their activity seems to continue up to 40 hours before the cumulative curve reaches a plateau. Concerning the SAP cubes that were exposed to wind, there seems to be a delay in the SAP activation. More specifically, the SAPs were activated around 17.5 hours, which indicates a 3-hour delay as seen in Figure 2-right.

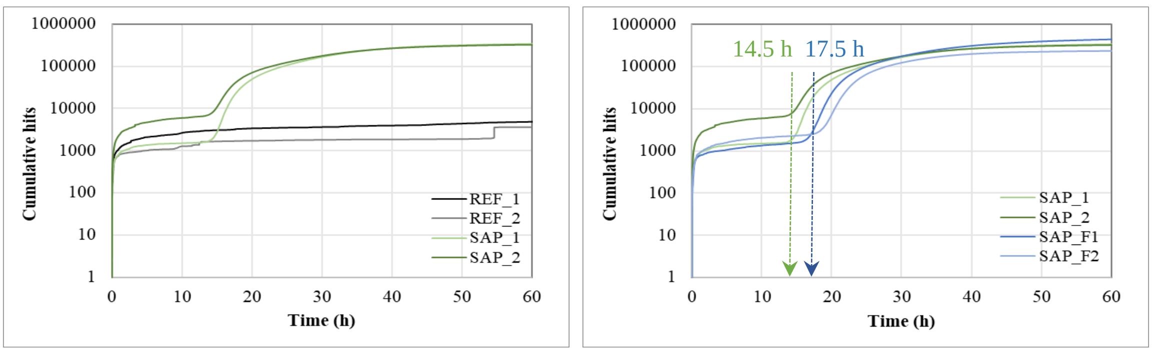


Figure 2. AE cumulative activity of the investigated specimens.

To further investigate the influence of environmental conditions (wind) on the SAP activity, the Moving Average (MA) of the peak frequency obtained from the Fast Fourier Transform (FFT) and the amplitude evolution were investigated. The results showed that the SAP_F specimens presented higher amplitudes up to 15 hours, compared to the SAP specimens. After 15 hours, SAPs started to activate and the amplitudes of the wind-exposed SAP concrete were lower than the ones of ambient SAP concrete, as Figure 3 shows. The opposite trend was observed for the peak frequency, which was higher generally for the wind-exposed specimens. Initially, the peak frequency increases up to 6 hours and then reaches values above 60 kHz up to the SAP activation. For the ambient SAP specimens, those initial values are around 30 kHz, almost half of those of the SAP_F.  After the SAP activation, the peak frequency fluctuates between 80-100 kHz for the SAP_F specimens, and between 60-80 kHz for the SAP specimens. The air imposed by the fan resulted in a lower temperature, which in turn resulted in a retardation of hydration. Therefore, SAPs retain their entrained water for longer. Internal relative humidity measurements could be helpful in this case, to better understand the humidity condition in the matrix interior.

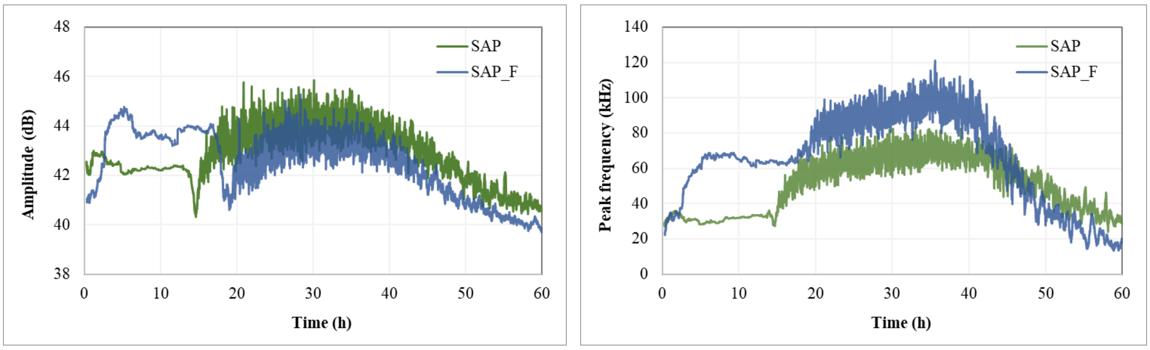


Figure 3. Moving average (per 500 hits) of the amplitude and peak frequency evolution in time of SAP and SAP_F.

The postponement of the SAP activity prolongs internal curing, which in turn will result in better mechanical properties, due to the ongoing formation of new hydration products. This delay in activity was passively captured by the sensors, without interfering with the material. This demonstrates that early-age internal processes in concrete can be assessed, and projections towards the final mechanical properties could be made using the early-age AE data.

### 3.2 SAPs shrinkage mitigation by DIC

To validate the quantity of the shrinkage mitigation by the SAPs, DIC was applied on the surface of the reference concrete and concrete containing SAPs. The settlement and strain evolution were obtained. The settlement was measured as the vertical displacement divided by the thickness of the sample. The calculated strain is the Lagrange strain $\varepsilon_{xx}$ which is taken as the average strain of DIC's area of interest. The negative strain values represent shrinkage, while positive values indicate expansion. Figure 4 shows the surface settlement and strain evolution of a REF and a SAP sample. The results showed that settlement and shrinkage were less profound for the SAP specimens compared to the reference ones. SAP specimens showed 1.5 times less shrinkage and half the settlement of that of the REF specimen. This confirms that SAPs successfully mitigated shrinkage and volumetric changes.

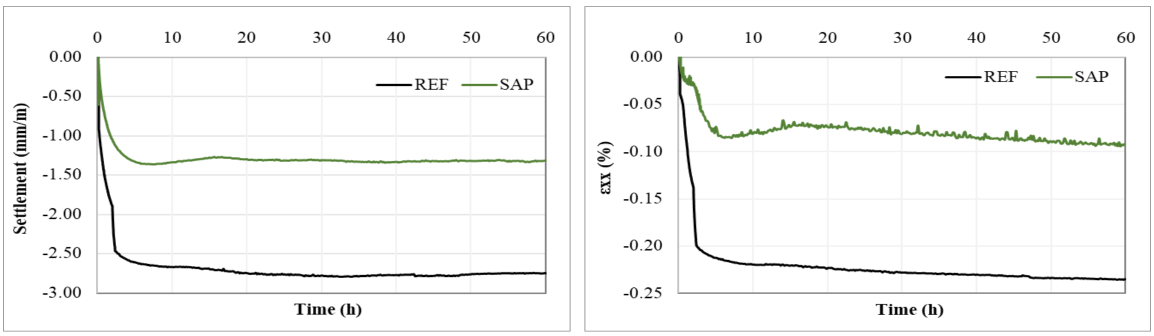


Figure 4. Surface settlement and shrinkage evolution of reference concrete and concrete containing superabsorbent polymers.

In the graphs, one can observe that settlement and strain curves of SAP concrete show a slight change in curvature, which begins between 7-8 hours after mixing. At that period, the absolute values of strains and settlement start to decrease, indicating volume expansion. This could be linked to the SAPs releasing part of their entrained water. According to a previous study done by Snoeck et al. [9] concerning the release of water from the SAPs towards the cementitious matrix, the results showed that SAPs release a small amount of their entrained water after the final setting is reached. Then the free water is consumed, causing the SAPs to release the rest of the entrained water, which is the reason for the increased AE activity.

A more accurate representation of the strain state at 50 h after casting [50 + (10-14) min after water is added to the dry material] is depicted in Figure 5. The specific time was chosen because at 50 h most of the early-age shrinkage has already taken place and the SAP action had already been completed. The whole surface of the 150x150 mm specimen was monitored, and a slightly smaller part of 140x140 mm is depicted, to avoid the irregularities imposed on the sides by the mold. The purple areas, dark and light blue represent shrinkage, while the red, yellow, and green areas represent expansion. The shrinkage is once again more evident for the REF specimen, while the SAP specimen exhibits very few shrinkage areas.

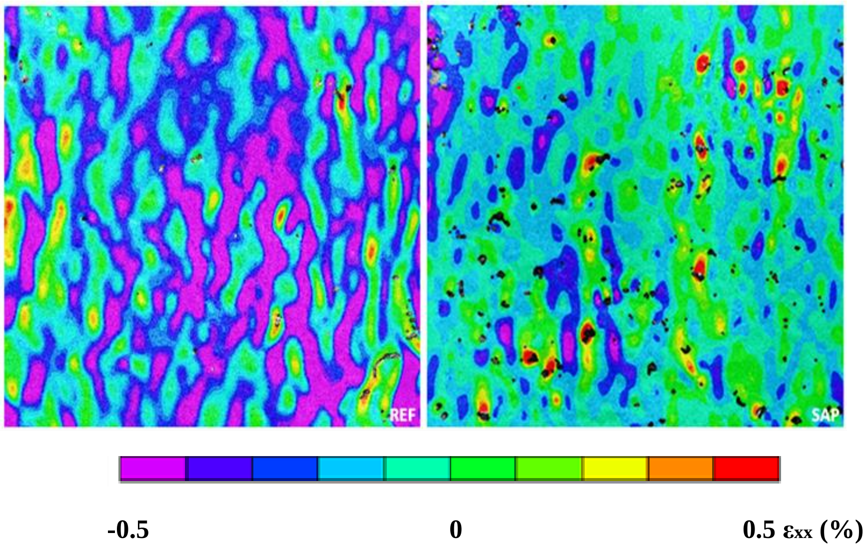


Figure 5. Lagrange strain $\varepsilon_{xx}$ at 50 h after casting for REF concrete (left) and SAP concrete (right).

## 4. SUMMARY AND CONCLUSIONS

The early-age behavior of fresh reference concrete and concrete containing SAPs was monitored in this study by combining the techniques of AE and DIC. The motivation is to obtain real-time information on the different ongoing processes in fresh concrete using AE and compare the results to concrete containing SAPs. In the first series of experiments, reference concrete and concrete containing SAPs were monitored by AE and DIC to validate the shrinkage mitigation by the SAPs. In a second series of experiments, SAP concrete is subjected to different environmental conditions (ambient and wind conditions), and AE was used to collect real-time data on the changes in the SAP activity.

The analysis of the AE activity showed that the windy conditions caused the SAPs to retain their entrained water for longer. This could be attributed to the fact that wind lowers the external temperature, delaying therefore hydration. More specifically, internal curing started approximately three hours later for the wind-exposed SAP concrete than the ambient SAP concrete. The SAP concrete subjected to windy conditions exhibited lower amplitudes before the onset of the SAP activity, and higher amplitudes after that, compared to the ambient SAP concrete. Regarding the peak frequency, as obtained from the Fast Fourier Transform, wind-exposed concrete is characterized generally by higher peak frequency values than ambient SAP concrete.  The SAP action fluctuates around 80-100 kHz when exposed to wind, and around 60-80 kHz at ambient conditions. Finally, the shrinkage mitigation by the SAPs was successfully captured by DIC. SAP concrete presented half the settlement and one-third of the shrinkage of reference concrete.

## ACKNOWLEDGMENTS

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