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ACOUSTIC EMISSION FOR MONITORING OF FRACTURE IN CEMENTITIOUS SANDWICH PANELS AND FRESH CONCRETE

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Abstract: Acoustic emission (AE) is commonly utilized for the characterization of the damage condition of construction materials and structures. The damage mechanisms generate elastic signals with unique characteristics that enable their identification, a phenomenon observed across various fields like cementitious materials, masonry, polymer composites, and metals. Additionally, AE's sensitivity allows for the detection of indicators even prior to visible signs of damage, thereby providing early data for structural health monitoring. Recent findings have demonstrated that early AE parameters are correlated to the original strain field, enabling projections regarding the final dominant damage or fracture mode. This capability enhances real-time evaluations of material conditions before the load-bearing capacity is compromised and holds promise for in-situ applications. This study emphasizes emerging trends that illustrate the potential of integrating AE with other techniques to effectively monitor and predict the behavior of structural materials. Examples are taken from the complicated behavior of lightweight fiber-reinforced cementitious sandwich panels during bending, as well as fresh concrete curing with a plethora of mechanisms including shrinkage cracking.

1 INTRODUCTION

Acoustic emission (AE) is a technique that has been successfully used in concrete engineering for fracture monitoring and early warning against failure. As a phenomenon, AE is characterized by the transient elastic waves that propagate by a sudden release of energy in a material, which in most cases is related to fracture events. AE waves are recorded as electric signals through piezoelectric sensors usually applied on the surface of the media under inspection [1].

The sensitivity of AE to micro-cracking has been established in different material fields. Indicative examples from cementitious media can be found in [2,3] where microcracking comes from mechanical loading or drying shrinkage in concrete.

Despite contributions from the medium (stiffness, damping) and the sensor's frequency preference, the resulted AE wave is indicative of the original motion of the crack tip. Therefore, it contains information on the original source or failure mechanism. In general, the different fracture modes have been simply classified between tension and shear [4]. In reality, depending on the complexity of the material or component, there can be several different mechanisms, like matrix cracking, delaminations, debondings, fiber pull-out, fiber rupture, concrete crushing among others. Due to the nature of concrete, tensile mechanisms like the cracking of the brittle matrix are activated at lower load, while shear mechanisms like debonding of reinforcement or fiber pull-out are more active at higher load closer to the upcoming failure. Fig. 1 illustrates indicative AE waveforms from a tensile and a shear event. The waveforms are different due to the different displacements occurring during tensile or shear events. Tensile cracks result mostly in longitudinal waves, while shear ones result in transverse waves which are slower, resulting in later arrivals within the waveform. Therefore, tensile events result in shorter AE waveforms, including shorter rise time (RT), lower RA value (RT over A, amplitude) and usually higher frequencies than shear events.

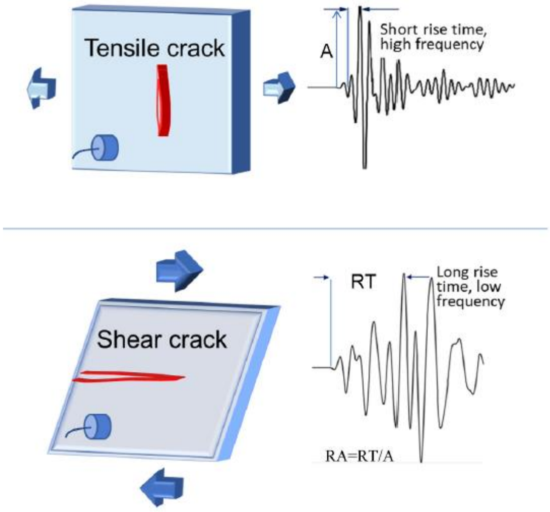

Figure 1. Schematic representation of cracking modes and corresponding AE waveforms [5].

Furthermore, the sensitivity of AE to the attoJoule energy scale events enables not only to monitor damage after it becomes obvious, but much earlier, being essentially sensitive to the developing strain field and capable of pinpointing the fracture mechanism that is first activated or what could be considered as the weakest link of the system.

As aforementioned, the first example described in this paper is the examination of textile reinforced cement (TRC) sandwich panels, followed by the monitoring of fresh concrete shrinkage cracking.

2 LIGHTWEIGHT CEMENTITIOUS SANDWICH PANELS

Concrete sandwich panels consist of two TRC skins and an insulating core in between [6]. Despite the clear advantages of TRC sandwich technology over heavy, steel-reinforced bulk concrete, its failure mechanisms are quite complex. In addition, a weak interlaminar bond between the skins and the insulation would result in premature debonding and reduce the loadbearing capacity of the whole structure [6]. These defects can be induced during operation but also during manufacturing and go unnoticed as there is no widely used methodology for quality inspection of the sandwich panels.

In order to examine the effect of the weak interphase on the fracture behaviour of sandwich concrete beams, oil was applied in the center of specific samples during casting to eliminate possible bonding between the insulating foam and the cement. A photograph of the mechanical four-point bending test can be seen in Fig. 2. The compromised bond proved very influential as it reduced the load bearing capacity by more than 50% compared to the reference healthy sample [6].

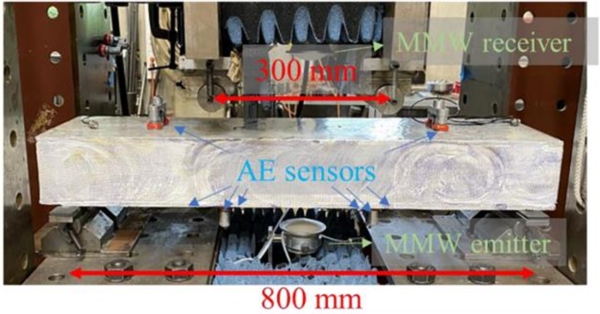

Figure 2. Photograph of the TRC sandwich panel under four-point bending.

Concerning the AE behavior which is the main focus of this article, Fig. 3 shows the “average frequency”, AF vs. RA graph for reference and for compromised specimens from activity taken during the initial 2 mm of the mid-span displacement. There is a consistent difference since the debonded specimens exhibit lower frequency by 50 kHz in average and approximately 40% longer RA value than the reference. The explanation is related to the strain field that is developed in the two cases. In the reference case, the damage is initiated by cracks at the tensile side, resulting therefore, in higher frequencies and shorter signals. On the other hand, in the debonded specimens, the same external loading pattern induces high shear stresses near the tip of the debonded area. This leads to debonding extension, and eventually to failure due to separation between the core and the skin, without causing considerable cracking. These differences are clear from the early part of the test at less than 10% of the maximum load value, and before any observable damage is sustained. They suggest that in complex components like TRC sandwich panels, AE is sensitive to the initial defect and strain distribution and can identify the failure mechanism that will eventually lead to the main fracture.

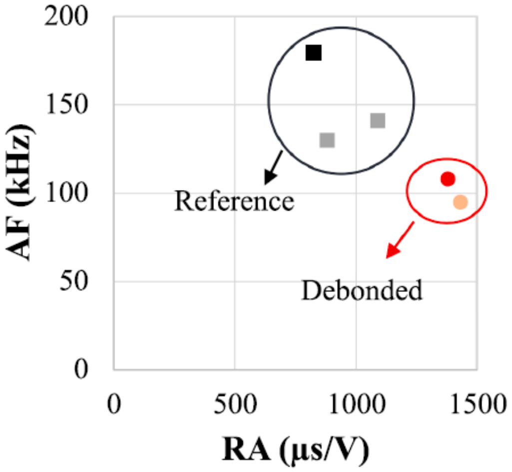

Figure 3. AF vs. RA for different types of sandwich panels.

This result is confirmed by DIC strain maps that indicate that for a reference panel several cracks occur at the bottom TRC skin (see Fig. 4a), while in specimens with initial debonding, cracking is minimal and the specimen fails with a horizontal delamination (Fig. 4b).

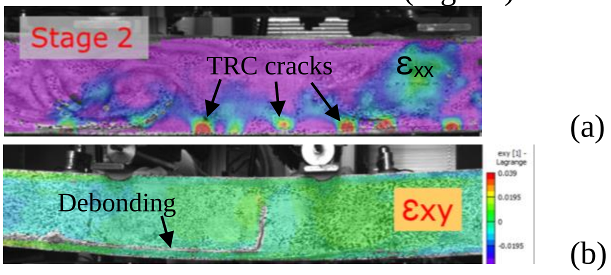

Figure 4. (a) Normal strain ε_{xx} in reference sandwich panel, and (b) shear strain ε_{xy} at a debonded panel.

3 FRESH CONCRETE MONITORING

Monitoring of fresh concrete is an emerging field due to the importance of the early phase of the material's life to its overall performance. In also enables "active control" of curing, a groundbreaking concept that allows external interventions based on the needs of the material as long as the nature of the material permits [7]. The mechanisms primarily investigated were the early hydration phase and early-age shrinkage cracking. Due to the several potentially overlapping processes occurring in fresh concrete there is always a background of AE activity (settlement, thermal expansion, internal curing) and it is not straightforward to discriminate between the different mechanisms. However, cracking can be identified due to the high energy bursts that it produces, as seen in Fig. 5a, due to the sudden release of energy. These bursts are not present in concrete with superabsorbent polymers (SAPs) that mitigate shrinkage and related cracking (see Fig. 5b).

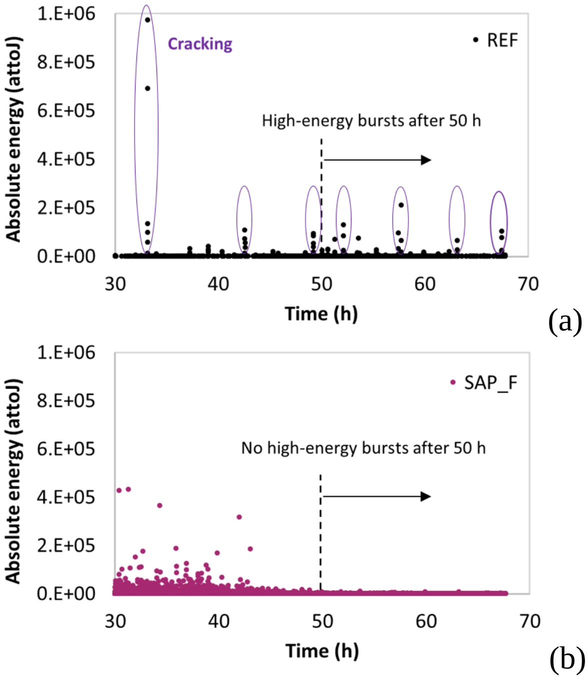

Figure 5. Energy of AE events for (a) reference and (b) SAP concrete [8].

Intensity-related parameters of the waveforms seem to be good descriptors to separate the cracking from different mechanisms. Fig. 6

shows the probability density function of amplitude for different mechanisms. Although several mechanisms show overlapping distributions and their real time classification would not be straightforward, the signals from cracking present a distinct trend. Their distribution is almost by 30 dB shifted to higher values, enabling reasonable separation. Other time domain parameters like energy and duration are also strong descriptors [8].

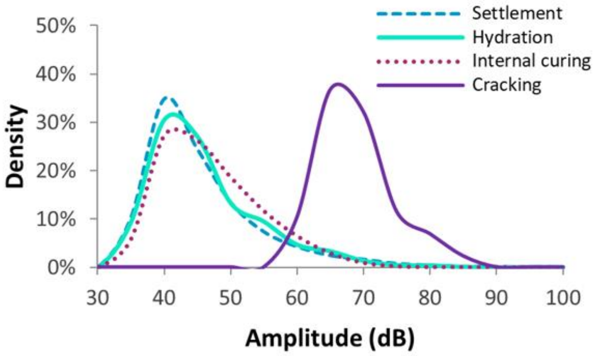

Figure 6. Probability density distribution for AE signals coming from different mechanisms in fresh concrete

It is reasonable to assume that since cracking is a detrimental mechanism, higher cumulative AE energy associated to cracking bursts during the first days of curing, would be a negative predictor for the final compressive strength of concrete. Fig. 7 shows the correlation between the cracking AE energy and the 28 days compressive strength for different reference specimens. It is shown that specimens with higher relative cracking AE energy exhibit strengths below 80 MPa, while as the AE cracking energy drops, the compressive strength increases close to 90 MPa.

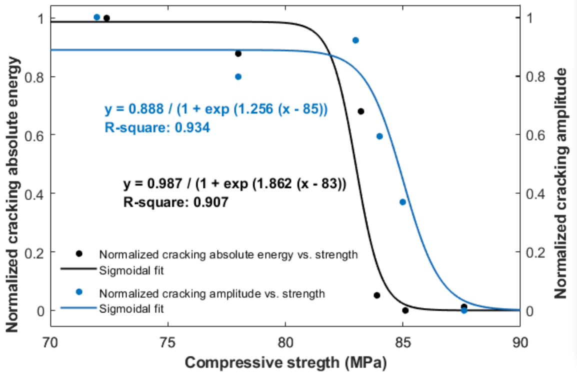

Figure 7. Normalized absolute energy and amplitude of micro-cracking AE vs. compressive strength of REF concrete at 28 days.

This shows that AE monitoring of early age concrete can lead to predictions for the final performance. Furthermore, it can also lead to the possibility of active control [7], when detrimental indicators are unfolding making external interventions possible to steer curing when necessary.

5 CONCLUSIONS

AE has the capacity to characterize the low intensity, different damage mechanisms, offering predictions about the macroscopically observed phenomena. In both examples described in this paper, AE proved very sensitive to the early manifestation of fracture phenomena. Specifically, for the lightweight cementitious sandwich panel, AE indices from the start of the loading were very characteristic of the type of damage (cracking of the TRC skin vs. debonding between core and skin). This is due to the different wave modes that are excited by the shear or tensile strain field when the energy is released as preliminary manifestation of the corresponding damage mechanism. In the field of fresh concrete, AE being sensitive to the attoJoule scale can record AE due to different processes. AE attributed to early age cracking, identified by energy parameters seems to be negatively correlated to the 28 days compressive strength. In general, the AE activity is a reflection of the mechanical behavior well before any other measurable indication of damage is available, offering therefore, crucial information for the structural integrity of the material.

ACKNOWLEDGEMENT

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