Influence of the Water and Aggregate-to-Cement Ratio on the AE Activity of Fresh Concrete

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Abstract. The key point for an optimized and long lasting construction with certified high quality for the entire service life is the determination of the early age material properties and the monitoring of their evolution. Despite the fact that concrete is the most widely used construction material, conventional techniques for the estimation of the mechanical properties are only applicable to the hardened material. Moreover, concerning the fresh concrete examination, the already existing techniques provide only qualitative information, are not representative over the full time period of curing, setting and hardening or have limited accuracy and repeatability. Therefore, the application of nondestructive evaluation (NDE) seems the only way to accomplish quality control from the fresh stage of the concrete material. In this study, the acoustic emission (AE) and ultrasonic pulse velocity (UPV) nondestructive testing techniques (NDTs) are employed in order to investigate the influence of the mixing proportions on the early age concrete’s behavior and the development of its stiffness. The intermediate goal concerns the deep understanding of the complex mechanisms being present in cementitious concrete specimens during hydration while the final goal is the establishment of the optimal water to cement (w/c) or aggregate to cement ratio (a/c) which ensures higher strength and durability. For this reason, several tests are performed in the laboratory with a varying w/c ratio (0.35, 0.5 and 0.65 respectively) or varying a/c ratio from 0 (cement paste) to 5. The investigation concludes that AE during hydration of concrete is due to several phenomena like segregation, formation/migration of air bubbles, formation of hydrates and also influenced by phenomena such as the wave propagation including scattering, attenuation and the viscosity of the matrix. Additionally, it is found that the development of AE activity during the first 24 hours is faster for the mixes containing lower w/c or higher a/c ratio, similarly to the rate of hydration curves known from literature. Finally, through this work, it is made clear that the RA and average frequency (AF) waveform parameters can be efficiently used for quality characterization, since significant differences between the mixes are observed.

Introduction

The increasing use of blends of binders, chemical admixtures and air entraining agents renders nowadays the control of cement based materials during their production and execution more and more imperative. Furthermore, the control of high performance products in the light of structural safety is, more than ever before, necessary for assuring higher quality, uniformity and better durability.

Despite the high importance of quality control, the properties of cement based materials in the fresh and hardening state are still being measured with conventional
methods, which are not objective since the results are highly dependent on the measuring device and the measuring procedure. As an example, the setting and hardening of cement is determined by the Vicat needle, which provides arbitrary values that cannot be correlated with the properties of concrete in the hardening state and are only useful for comparison of different cementitious materials. Moreover, concerning the measurement of workability, many tests exist such as the slump test, the compaction test and the penetration test. However, none of them can successfully predict the “real” workability at the site, for instance during slip forming [1].

Therefore, among material producers, suppliers, researchers and end users, it is made clear, that objective and scientifically based rather than empirical test methods for the continuous monitoring of material properties from the fresh until the hardened state are needed [2]. In this direction, nondestructive testing techniques [3] and particularly the Acoustic Emission (AE) technique have been developed [4-5]. The latter is based on the recording of acoustic waves and the analysis of their most significant features which are altered according to the mix design and/or the hardening process.

Other features depending on the composition of a mix include damping, dispersion, energy transport and frequency spectrum that can also be measured and quantified [6-8]. Using stress wave techniques, changes of the mix expressed by changes of the amount (concentration) of a component can also be detected.

Passive monitoring by acoustic emission (AE) has been used in certain cases to quickly estimate the consistency of fresh concrete during mixing, to estimate the degree of compaction as well as to monitor micro-cracking due to drying shrinkage [5, 9]. In this study, the aforementioned technique is used during the first 24 hours after mixing of fresh concrete specimens in order to investigate whether the monitoring of the very early stage of the material’s life is possible and whether the water to cement (w/c) ratio or aggregate to cement (a/c) ratio influence the AE activity of fresh concrete. As will be shown in Section 4, processes like segregation, air and water migration, formation of solid hydration compounds and cavitation are captured [10-11], while a link between early age AE parameters and mechanical properties at the age of 28 days is also established.

2. AE technique

When the internal structure of a material undergoes irreversible changes due to cracking, plastic deformation, temperature gradients, mechanical forces or, in the case of fresh concrete, segregation and migration, elastic waves are generated as a result of several acoustic emissions [12-13]. The phenomenon of radiation of acoustic waves as well as the technique measuring this phenomenon is called Acoustic Emission (AE). The emitted waves propagate in spherical shapes from the source location to the whole volume of the solid resulting in small surface displacements, which are recorded by suitable piezoelectric transducers.

In Structural Health Monitoring applications, AE is typically used to detect, locate and characterize damage based on the analysis of its waveform parameters, as shown in Fig. 1 [14-16]. The amplitude (A), measured in dB or Volt, is the magnitude of the highest peak of the signal while the rise time (RT) expresses the delay between the first threshold crossing and the highest peak. The ratio of the rise time over the amplitude defines the RA value which is the inverse of the rising angle. The duration (DUR) describes the time distance between the first and last threshold crossing while dividing the threshold crossings (counts) with the duration provides the average frequency (AF) of the waveform, as shown in Fig. 1.
3. Experimental details

In the current experimental campaign, 20 concrete cubes of 150 mm size are prepared for the AE monitoring during the early hydration period of 24 hours as well as for compression tests at the age of 28 days. The specimens are composed of water, cement (CEM II/B-M 32.5 N), fine and coarse aggregates. The water to cement (w/c) ratio by mass is 0.35, 0.50 and 0.65 respectively, while the aggregate to cement (a/c) ratio by mass varies from 0 (cement paste) to 5.

For the fresh 24-hour AE examination, the liquid mixes are poured in metallic molds, while two R15 piezoelectric transducers with resonance frequency 150 kHz are continuously recording the behavior of fresh concrete. The sensors are fixed in the metallic surfaces using magnetic clamps, while a thin layer of Vaseline between the sensors and the latter is applied for the enhancement of acoustic coupling (see Fig. 2). Two cubes per concrete mix are monitored for statistical reasons. The acquired signals overpassing the amplitude limit (threshold) of 32 dB, are firstly preamplified with the aid of preamplifiers of 40 dB gain and then they are displayed in real time and stored for further analysis using a data acquisition system and a computer embedded AE software respectively. A similar study where AE measurements are obtained with sensors attached on the mold of a massive concrete structure is found in [17].

As already stated, the fresh concrete specimens monitored with AE for 24 hours are also subjected to compression with a hydraulic pressure machine at the age of 28 days for the determination of their compressive strength. The same day, before the destructive test takes place, the nondestructive ultrasonic testing is applied on the hardened concrete elements. The pulse velocity is measured with two probes of 50 kHz which are forming a through transmission arrangement providing indirect information on the stiffness of the materials.
4. Results

The RA value and AF parameters discussed in Section 2 are among the most powerful indicators of an AE waveform. They have been used extensively in recent studies concerning crack mode characterization (tensile or shear) and characterization of the severity of cracking (micro-cracking or macro-cracking) [14-16]. In this study, even though the very early stage of concrete hardening is monitored, where at least for the first few hours the material is liquid and no cracking takes place, it is deemed worthy investigating the time evolution of the aforementioned parameters, as described in relevant recommendations [18]. Herein, it should be mentioned that it is the first time that these AE parameters are applied in such a fresh stage of the material’s life showing at the same time strong quality characterization potential.

Fig. 3 presents the evolution of the RA and AF waveform parameters as a function of time for the first 24 hours after concrete mixing. As shown in this figure, there is a clear difference among the different mix designs expressed by the different w/c ratios. For the longest part of the test, the concrete specimen containing the lowest water content (w/c=0.35) is characterized by higher RA and lower AF values compared to the one with the highest water content (w/c=0.65), while the specimen of w/c=0.5 is always in between the two. Unlike the case of cracking of the hardened material, in this case, there is no direct and easy explanation, since during hydration a sum of processes are occurring, including bleeding, segregation, migration of gas and water, formation of solid compounds and cavitation. Assuming that all these processes are happening in all the examined concrete specimens in a weaker or stronger degree and that the boundary and environmental conditions are the same, the change of the waveform characteristics is clearly attributed to the different water contents influencing wave propagation. Finally, it is worth noticing the fact that for all specimens (w/c=0.35, 0.50 and 0.65) the RA has an increasing tendency, while the AF exhibits a decreasing tendency. The results of Fig. 3 are presented using a moving average line considering moving samples of 75 points in order to find a trend from the cloud of scattered points appearing during hydration.
As it has already been mentioned, the emitted AE waves are propagating in all directions from the source location to the surface. There, the waves are recorded by the piezoelectric sensors creating the so called “AE hits”. The accumulation of hits in a small time window represents the rapidity of AE activity due to the ongoing mechanical or physical processes. Normalizing that activity with respect to the maximum of each mix design provides the degree of completed AE activity at a certain time instant or inversely the time it takes for a specific degree of AE activity to be completed. The latter is useful for comparison purposes among different concrete mixes, as shown in Fig. 4a. According to this figure, the activity is completed faster for the specimen containing a w/c ratio equal to 0.35, less fast for the w/c=0.50 specimen, while the slowest development of AE activity is seen for w/c=0.65. Moreover, it is interesting to notice from the same figure the shape of the curves which resembles the known hydration curves, thus implying that concrete’s hydration can be successfully monitored using the AE technique.

![Fig. 3](image1.png)

**Fig. 3.** 24-hours evolution of the RA and AF parameters during curing for different w/c ratio.

In the same direction, but using the absolute values of the cumulative AE hits, the concrete specimens characterized by different aggregate to cement ratios are compared in Fig. 4b. Based on this figure, it is clear that there exists a nice monotonic trend among the

![Fig. 4](image2.png)

**Fig. 4.** a) Normalized and b) total cumulative AE hits during the first 24 hours for concrete specimens with various w/c and a/c ratio respectively.

In the same direction, but using the absolute values of the cumulative AE hits, the concrete specimens characterized by different aggregate to cement ratios are compared in Fig. 4b. Based on this figure, it is clear that there exists a nice monotonic trend among the
presented cases. More specifically, the AE activity is the highest for the case of a/c equal to zero, while it becomes lower and lower as the aggregate to cement content becomes higher. The reason behind this is possibly the increased scattering caused by the inclusions, whose acoustic impedance is more significant compared to that of the liquid paste. Furthermore, during the tests, it has been observed that specimens with higher a/c ratio exhibit lower air bubble migration, thus leading to lower AE activity. Based on the results, it seems that segregation is not the dominant mechanism since the increased aggregate to cement ratio does not result in increased AE activity.

Since one of the aims of the current study is the correlation of early age AE parameters with the mechanical properties of concrete at the age of 28 days both Ultrasonic and compression testing is applied on the hardened specimens. The Pulse Velocity values provided from the first technique as well as the compressive strength provided by the second technique for the specimens with different w/c ratio are displayed in Table 1. On the same table, the RA and AF values calculated for a time window of one hour during the very early stage of monitoring (the fifth hour after mixing) are also contained. Comparing these values it is interesting to notice that there exists a strong correlation between the fresh and hardened states. The higher the RA value in the fresh state is, the higher the Pulse Velocity and the higher the compressive strength at the hardened state is. Moreover, it is found that the lower the AF is the higher the mechanical properties of the specimens are (stiffness and strength). The latter are very important since they offer the possibility to evaluate the mechanical properties of the hardened material by non-invasive monitoring of acoustic parameters during the early age and much earlier than mechanical tests can be applied (like the rebound hammer which requires a stiff surface).

Based on the values of Table 1, it needs to be highlighted that while pulse velocity exhibits a change of only 12% and compressive strength a change of only 28% between w/c=0.35 and w/c=0.65, the RA and AF values exhibit the significant changes of 82% and 45% respectively showing great characterization capacity and high sensitivity to the w/c change.

In the same framework, Table 2 contains the pulse velocity and compressive strength values (in m/s and MPa respectively) at the age of 28 days for the specimens with different aggregate to cement ratio. The same table contains as well the total number of AE hits as obtained by accumulating the AE activity for 24 hours (see also Fig. 4b). As it is obvious from this table, there is again a significant link between the early age AE parameter and the mechanical properties of the hardened material. The lower the recorded AE hits, which correspond to the highest aggregate content, the higher the stiffness and compressive strength is.

Even though it is difficult to directly explain these correlations which most probably are attributed to wave propagation phenomena rather than differences in the actual sources, it is encouraging that these correlations exist and allow projection to the final mechanical properties.

Table 1. Mechanical properties at the age of 28 days and their correlation with early age AE parameters for concrete specimens with various w/c ratio.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Pulse velocity (m/s)</th>
<th>Compressive strength (MPa)</th>
<th>Average RA [5-6h] (μs/V)</th>
<th>Average AF [5-6h] (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/c=0.35</td>
<td>4704</td>
<td>42</td>
<td>9319</td>
<td>74</td>
</tr>
<tr>
<td>w/c=0.50</td>
<td>4557</td>
<td>39</td>
<td>2673</td>
<td>95</td>
</tr>
<tr>
<td>w/c=0.65</td>
<td>4143</td>
<td>30</td>
<td>1617</td>
<td>108</td>
</tr>
</tbody>
</table>

6
Table 2. Mechanical properties at the age of 28 days and their correlation with early age AE parameters for concrete specimens with various a/c ratio.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Pulse velocity (m/s)</th>
<th>Compressive strength (MPa)</th>
<th>AE hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>a/c=0</td>
<td>3363</td>
<td>36</td>
<td>5274</td>
</tr>
<tr>
<td>a/c=1</td>
<td>3931</td>
<td>42</td>
<td>4744</td>
</tr>
<tr>
<td>a/c=2</td>
<td>4185</td>
<td>37</td>
<td>1713</td>
</tr>
<tr>
<td>a/c=3</td>
<td>4266</td>
<td>38</td>
<td>1665</td>
</tr>
<tr>
<td>a/c=4</td>
<td>4451</td>
<td>40</td>
<td>1107</td>
</tr>
<tr>
<td>a/c=5</td>
<td>4505</td>
<td>44</td>
<td>843</td>
</tr>
</tbody>
</table>

5. Conclusions

The present work deals with the influence of the water to cement ratio and the aggregate to cement ratio on the AE activity of fresh concrete. Nine concrete mixes are considered revealing significant differences among them based on the RA and AF waveform parameters of the AE technique as well as on the cumulative AE hits. The RA and AF parameters are applied for the first time in such an early stage of a material’s life and provide great characterization potential. Furthermore, comparing the RA and AF values obtained at a very early age with the pulse velocity and compressive strength at the age of 28 days it is found that the evaluation of the mechanical properties is possible if the behavior of the material is passively monitored with the AE technique during the first 24 hours. The current work is the first step towards the use of the AE nondestructive technique for quality control and characterization of fresh cement based materials.

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References


