CAN ACOUSTIC EMISSION BE USED TO DETECT ALKALI SILICA REACTION EARLIER THAN LENGTH CHANGE TESTS?

Mohammad Pour-Ghaz[1,2], Robert Spragg[2], Javier Castro[2,3], Jason Weiss[21]

[1]North Carolina State University, Raleigh, NC, USA

[2]Purdue University, West Lafayette, IN, USA

[3]Catholic Pontifica University, CHILE

Abstract

The assessment of potential alkali reactivity in concrete materials can be difficult and time consuming. Traditionally, length change measurements have been a popular choice for evaluating how reactive and expansive a material can be. This paper presents the results of an experimental study that questions whether acoustic emission (AE) can be used to detect and quantify damage due to ASR in mortar specimens. In this paper conventional length change measurements were performed along with passive acoustic emission measurements. The goal of this work was to compare the results of these two test methods to evaluate whether acoustic emission is a potential method for rapid assessment of damage due to ASR. It was found that by using acoustic emission, cracking of the specimens due to ASR can be captured significantly earlier than the occurrence of substantial length change. The results of acoustic emission show that with increased extent of cracking, the attenuation of the elastic wave increased. This is in part due to the formation of cracks and likely in part to the formation of gel. The wave characteristics of the acoustic events are being studied in an attempt to differentiate between formation of different types of cracks and opening of the cracks due to the initial formation in aggregates, in the ITZ, and in the matrix. While still in its infancy, it appears that the use of acoustic emission may have some beneficial aspects for ASR evaluation.

Keywords: acoustic emission, alkali silica reaction, cracking, expansion, geometry, ICAAR, testing

1 INTRODUCTION

The alkali-silica reaction (ASR) is a chemical reaction that occurs when alkalis (coming primarily from the cement) react with certain amorphous silica components (coming primarily from the aggregates) [1]. This chemical reaction results in formation of an alkali-silica gel, which expands in the presence of water. This expansion can result in micro-cracking of the aggregates which is followed by cracking at the aggregate-matrix interface and in cement paste matrix. The presence of cracks accelerates the fluid ingress thus further accelerating the ASR reaction and damage [2].

While acoustic emission has been used to detect cracking in concrete due to mechanical damage [3-13], freezing damage [3, 4, 14, 15], corrosion damage [16-19], and restrained volume change [5, 20], few studies have been done to detect the influence of ASR on structures [21] and even less to determine if ASR damage development could be detected. This work began to determine whether acoustic emission may be feasible as a method to detect damage development due to ASR [22]. As a proof of concept, previous research used acoustic emission to detect and quantify cracking due to expansion of polymeric aggregates in cement-based composites [23]. Although the mechanics of the damage caused by expansion of polymeric aggregates due to thermal loading and damage caused by ASR are similar conceptually, the underlying mechanism is substantially different [24]. In polymer aggregate-cement composite (used in the proof of concept studies [23]) the damage was caused by a uniform expansion of the spherical/cylindrical inclusions. On the other hand, the damage observed in mortar samples undergoing ASR is caused by the expansion of gel in the

[1] Correspondence to: wjweiss@purdue.edu

crack or aggregates or on the surface of the irregular aggregate. Furthermore, the formation of gel around the aggregates is not necessarily uniform and aggregates are not cylindrical or spherical. The deposition of gel within the cracks may also cause a wedge-splitting type force on the surrounding matrix [25]. These factors can cause a non-uniform stress development and cracking.

It is the hypothesis of this paper that acoustic emission can be used as a rapid method of assessment of susceptibility of a cement-based material to ASR. This hypothesis is based on the assumption that cracking must precede the substantial portion of the volume change due to ASR. If the acoustic activity can be detected before length change occurs, it will be faster than current length change measurements. It may also be able to be used to separate different damage mechanisms [3, 4, 14], therefore improving our understanding of ASR damage formation.

2 MATERIALS AND METHODS

2.1 Materials and Mixture Proportions

Mortar specimens were prepared using ordinary portland cement (OPC, Type I) with a water-to-cement ratio (w/c) of 0.47 and 55% fine aggregate by volume. The fine aggregates that were used in this study showed more than 0.1% expansion after three days when tested according to ASTM C1260 [26] so it is clear that these are very reactive aggregate (0.67% after 14 days and 0.81% after 28 days). The source of the reactive fine aggregate was Jobe, Texas [27]. Mixing was performed according to ASTM C192-06.

2.2 Sample Geometry and Preparation

Two series of experiments were performed in this study. In the first series of experiments (Series I) acoustic emission measurements were performed on samples that were companions to the length change measurements. In the second series of experiments (Series II) continuous length change measurements were performed while the acoustic emission was measured on the same sample.

Series I – Separate Length Change and Acoustic Measurement Samples

Cylindrical specimens were prepared with a length of 11.0 inches (27.94 cm) and five different diameters of 1.0 inch (2.54 cm), 1.5 inch (3.81 cm), 2.0 inch (5.08 cm), 3.0 inch (7.62 cm) and 4.0 inch (10.16 cm) respectively. Figure 1 shows a photograph of the specimens with different geometries. A total of four specimens were used for each diameter cylinder in performing the length change measurements. The cylindrical specimens were cast inside PVC pipes. After 24 hours the PVC pipes were cut and samples were demolded. The lengths of the specimens were adjusted to an appropriate length by cutting so that they would fit in a 10 ½ inch (26.67 mm) comparator after the installation of the pins. At both end, a small hole was drilled at the center of the cross-section of the specimen and a pin (the same pin as that commonly used in ASTM C1260 testing) was installed using high strength epoxy. The entire end surface of the specimens (i.e., the circular section) was then sealed with water-resistant epoxy (see Figure 1). Specimens were kept sealed for 24 hours to ensure that the epoxy gained sufficient strength. Specimens were then placed in water for 24 hours and then moved to 1 N NaOH solution (ASTM C1260). For all the specimens the same solution-to-sample volume ratio (4.0$\pm$0.5) prescribed by ASTM 1260 was considered. Specimens were placed at 38$\pm$1^{o}C (100$\pm$1.8^{o}F) and length change measurements were performed. The same curing and measurements conditions were used for prismatic samples. For the acoustic emission tests one end of each cylinder was completely sealed using water-resistant epoxy. The cylinders were 4.0 inch (10.16 cm) long and only select diameters were tested. On the other end, a waveguide was mounted at the center of the cross-section using water-resistant epoxy and the rest of the cross-section was sealed with the same epoxy. Sealing of the samples at both ends ensured radial fluid transport (which can be modelled as axi-symmetric). The samples were wrapped and sealed with a plastic sheet and left in a chamber at 23$\pm$1^{o}C (72$\pm$1.8^{o}F) for 24 hours to ensure that the epoxy is harden. Samples were then submerged in water for 24 hours at 38$\pm$1^{o}C (100$\pm$1.8^{o}F). Water was replaced with 1N NaOH solution after 24 hours and acoustic emission measurements started.

Series II – Length Change and Acoustic Measurement on the Same Sample

In the second series of experiments one specimen diameter was tested with two samples for repeatability (Figure 2). Cylindrical 14.0 inch (35.56 cm) tall specimens with 4.0 inch (10.2 cm) diameter were used. A 3.0 inch (7.62 cm) long 0.375 inch (0.95 cm) diameter threaded rod was inserted at the centre of the PVC cap and secured in position using epoxy. The threaded rod was positioned in such a way that after casting 1.0 inch (2.5 cm) of its length would be embedded in the specimen. After 24 hours the PVC pipe was cut and the specimen was demolded. The entire cross-section of the specimens (containing inserted threaded rod) was sealed using a water-resistant epoxy. On the other end, two stainless steel waveguides (with 1.0 inch (2.54 cm) diameter) and a stainless steel rod (with 1.5 inch (3.81 cm) diameter) which was used as LVDT rest-point were mounted using water-resistant epoxy and the rest of the cross-section was sealed with the same epoxy (Figure 3a). After demolding, the samples were wrapped with a plastic sheet and left in a chamber at 23$\pm$1^{o}C (72$\pm$1.8^{o}F) temperature for 24 hours to ensure that the epoxy gained sufficient strength (Figure 3b). Samples then were placed in water for 24 hours at 38$^{o}\pm$1^{o}C (100$\pm$1.8^{o}F). Water was replaced with 1N NaOH solution after 24 hours and acoustic emission and continuous length measurements were performed at 38$^{o}\pm$1^{o}C (100$\pm$1.8^{o}F). To ensure accurate length change measurements a rigid steel fixture was used to mount the specimen and LVDT. Figure 2 schematically illustrates the steel fixture and specimen.

2.3 Methods for Assessment and Analysis

Length change measurements using comparator

The length change of the cylindrical specimens was measured using a standard comparator (ASTM C490). Samples were submerged in water for 24 hours at 38$\pm$1^{o}C (100$\pm$1.8^{o}F) before being transferred to 1 N NaOH solution (ASTM C1260). The reference measurement (zero) was taken after 24 hours exposure to water (before exposing the samples to NaOH solution). During the first 30 days measurements were performed every 48$\pm$4 hours. Between 28 and 90 days measurements were performed once a week and biweekly afterward. Measures were taken to minimize thermal effects during the measurements.

Length change measurements using LVDT

For simultaneous length change and acoustic emission measurements a 0.3 inch (0.76 cm) model RDP D5-300AG LVDT was used. Readings were performed using a commercial data acquisition in 5 minute intervals. Before start of length change measurements the LVDTs were calibrated in the temperature at the testing temperature. The sample was placed inside the measurement fixture for 6 hours to enable the sample to approach thermal equilibrium before length change and acoustic emission measurement.

Acoustic emission measurements

Acoustic emission describes an engineering approach in which the acoustic wave that are generated as energy is released by cracking is measured. The acoustic sensors record the displacement (vibration, sound) this wave creates when it reaches the surface of the material [28]. The released strain energy that occurred due to cracking and/or micro-cracking can cover a wide range of inaudible and audible frequencies. These stress waves are known as acoustic waves [28]. Piezoelectric sensors are used to convert the captured acoustic waves into electrical signals. The strength of the signals (the amplitude and duration of the waves) generally depends on the amount of released energy, distance and orientation of the source with respect to the sensor, and nature of transferring media. The signals are then amplified and recorded in a data acquisition system. In addition to simply calculating the fact that a wave has been generated (AE counting), more detailed analysis can be performed on the wave-forms that are generated [18, 29, 30]. If area under the absolute value of the surface displacement is calculated it can be thought of as an 'energy' that is released and this calculated energy has been found to be proportional to the fracture energy [9, 10, 31].

A Vallen AMSY5 acoustic emission system was used in this study. In the first experiment where only the acoustic emission measurements were performed one acoustic emission sensor was used on each sample. In the second experiment (see Figure 2) where length change and acoustic emission measurements were performed two acoustic emission sensors were used on each sample and an average response was taken. Acoustic emission sensors were installed

on the waveguide using a silicon-based coupling agent that was found to be stable over the temperature range of the test. Broadband 375 kHz sensors were used in this study. The electrical signals from the sensors were processed and recorded. A noise threshold of 42 dB was considered for all acoustic emission sensors to exclude surrounding noise. Continuous passive recording was used for all the experiments from an age of 24 days. In general acoustic emission sensors placed on steel alone (i.e., not in contact with concrete) showed virtually no acoustic activity during this time period.

3 RESULTS

The experimental results show that the expansion of mortar specimens is influenced by sample geometry. Figure 4 illustrates specimens made using the same materials with different diameters. The specimens with a smaller diameter expand at a higher rate when compared to the specimens with larger dimensions. This may be caused by a more rapid fluid and ion ingress in specimens with smaller cross-sectional dimensions. Another contributing factor to smaller expansion of specimens with larger diameters may be the fact that in larger geometries the central core that resists the expansion is larger. Since the length of the exposure period for all specimens with different diameters was the same, the depth of the penetration of the water, ions and cracking should be the similar for all the specimens. It can be assumed that portion of the cross section of the cylindrical sample that ions have penetrated into is the expanding portion of the cross section (ring around the circumference) and the remaining area (core at the centre) is the area resisting against expansion. Since the resisting cross sectional area is larger in larger specimens their expansion is smaller. In Figure 5 the expansion of cylindrical samples with different sizes are plotted against inverse square root of radius of the cylinder (commonly done for problems related to diffusion). This plot shows that the expansion of cylindrical samples is approximately proportional to the inverse square root of radius.

Figure 4 illustrates one of the primary problems that the ASR community has continued to struggle with in developing rapid testing techniques. Simply stated, 'expansion experiments performed on real concrete samples' are going to expand more slowly than tests on the matrix alone or mortar due to the size of the geometry that must be used to 'get the aggregates' into the sample. As such, this work illustrates that there may be potential for test techniques that do not measure the overall sample behaviour but rather focus on the mechanisms that lead to the changes we see in sample length.

It is hypothesized that the use of acoustic emission has a major advantage when compared to an expansion test. This hypothesis is based on the assumption that cracking precedes the substantial portion of the volume change due to ASR. Furthermore, acoustic emission measures energy released due to cracking as opposed to the overall expansion of the material that occurs due to swelling and the cumulative effects of cracking. This may provide two additional benefits. First, all cracking does not lead to expansion in the same manner. For example, if one considers specimens tested in compression, it is known that micro-cracking that occurs in the pre-peak region of the loading has much less influence on volume change than does the opening of coalesced cracks that occur from approximately 80% of the peak load throughout the post peak [11]. Second, by monitoring acoustic emission it may be possible to listen to damage developing in the specimen or on the surface of the specimen before it leads to substantial expansion [5]. Therefore, it may be possible to detect damage in thin and thick elements with similar ease (neglecting complexities of wave loss etc). This could substantially overcome the size dependence that is observed in length change measurements. This may also have value in overcoming issues caused by 'directional restraint' caused by loading or reinforcing steel as cracking would be detected irrespective of its orientation [32, 33].

Figure 6 shows the cumulative acoustic energy normalized to the volume and surface area of the specimens with different geometries. In this Figure 6 the cumulative acoustic energy is plotted against expansion of the specimens. The initial rate of acoustic activity is not similar in all specimens. It can be seen that more energy is released in larger samples before a length change is measured.

Figure 7 illustrates the results of simultaneous length change and acoustic measurements (from a representative sample from a series of two samples). It can be seen in this figure that after approximately 5 days a discrete increase in acoustic energy is observed however this is not accompanied by a substantial length change. It is hypothesized that this

increase in acoustic emission activity is due to cracking in the aggregate which would occur as a predecessor to any cracking at the aggregate interface or in the matrix. This hypothesis is based on:

1) previous reports in literature[34],
2) limited optical microscopy that showed little to no matrix cracking (performed in this research but not reported in this paper) and
3) a slight difference between the acoustic characteristics between the early and later events

Following the initial activity there appears to be a decrease in the rate of acoustic activity between 5 and 12 days which is speculated to be related to the formation and deposition of gel which needs to occur to form a pressure before any new cracks would be generated.

After approximately 11-12 days the length change begins to show an appreciable increase in the rate of acoustic activity. This increase in acoustic energy is accompanied by the overall length of the sample starting to increase. It is expected that the cracking that is occurring during this period is likely caused by expansion of gel that is deposited in the previously formed cracks and around the aggregates resulting in interface and matrix cracking. This period of increased acoustic activity occurs for approximately 10 days after which time the rate of acoustic activity slows and a plateau begins to develop (after approximately 22 days at which time the acoustic testing was stopped).

The decrease in the rate of acoustic activity after approximately 20 days might be caused by one or combination of the following factors. These factors are consistent with other non-destructive testing methods and current research is attempting to determine the plausibility and magnitude of the following items.

1) The formation of new cracks has results in opening of more space where ASR gel can be deposited.
2) Due to excessive cracking the elastic waves are attenuated inside the sample and cannot travel easily in the sample and therefore are not captured by the acoustic sensors.
3) Formation of cracks and gel at the interface of the waveguides and specimen has resulted in increased attenuation and reflection of waves; therefore acoustic waves do not reach the acoustic sensor.
4) Loss of surface contact for some reason.

At this point it should be noted that after the second increase in the acoustic energy (after 22 days), the specimen has only expanded approximately 0.06% which is far below the criteria used in ASTM C 1260.

While more work is needed to fully explore these hypothesis presented in this section based on the observed data collected, the data clearly indicates that acoustic emission has the potential to be used as a rapid method of assessment of susceptibility of aggregates to ASR. At this point it should be noted however that this testing is limited to the mixture tested with a sand that is known to react rapidly [27]. Further work is needed to examine the potential benefits and short comings of the acoustic emission measurement approach when applied to different systems and to fully relate the acoustic signals to meso and microstructural behaviour, however the work shown here indicates that the technique may have merit and may have some particularly attractive features. For example, the results indicate that in addition to being a faster method, acoustic emission test is less sensitive to the geometry of the sample compared to the length change measurements.

4 CONCLUSIONS

This paper examined preliminary experimental results to determine whether acoustic emission may be able to be used as a potential method to detect cracking due to ASR. It was hypothesized that acoustic emission could detect cracking in samples before appreciable expansion occurred. The experimental evidence was consistent with this hypothesis. It was shown that using acoustic emission cracking due to ASR can be captured as early as five days after exposure of material to NaOH while the 0.1% expansion was detected after 18 to 20 days (both experiments were performed at $38\pm1^{o}C$ ($100\pm1.8^{o}F$)). Based on the results obtained in this study, it is anticipated that acoustic emission technique will also detect ASR when testing is performed at $80^{o}C$ according to ASTM C1260, or when a slower reacting aggregate is tested. More testing is required to fully understand the effect of reaction rate on detecting ASR using acoustic emission.

The influence of specimen size was also investigated. Generally, consistent with literature findings, specimens with smaller cross-sectional dimensions expanded much more rapidly than samples with a larger dimension. It was discussed that another potential benefit in that acoustic emission is that may be able to detect and quantify damage due to ASR in a manner that is not as dependent on sample geometry. This could suggest a method that is much better at assessing the behaviour of concrete samples which take notoriously long to test. Further testing however is needed to assess this hypothesis.

While further work is needed to examine the potential benefits and short comings of the acoustic emission measurement approach, this work has shown that the acoustic emission technique may have some applicability for detecting ASR damage and may have some particularly attractive features for testing larger elements that would be consistent with testing concrete.

5 ACKNOWLEDGEMENTS

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Figure 1: Photograph of specimens that were used for length change measurement

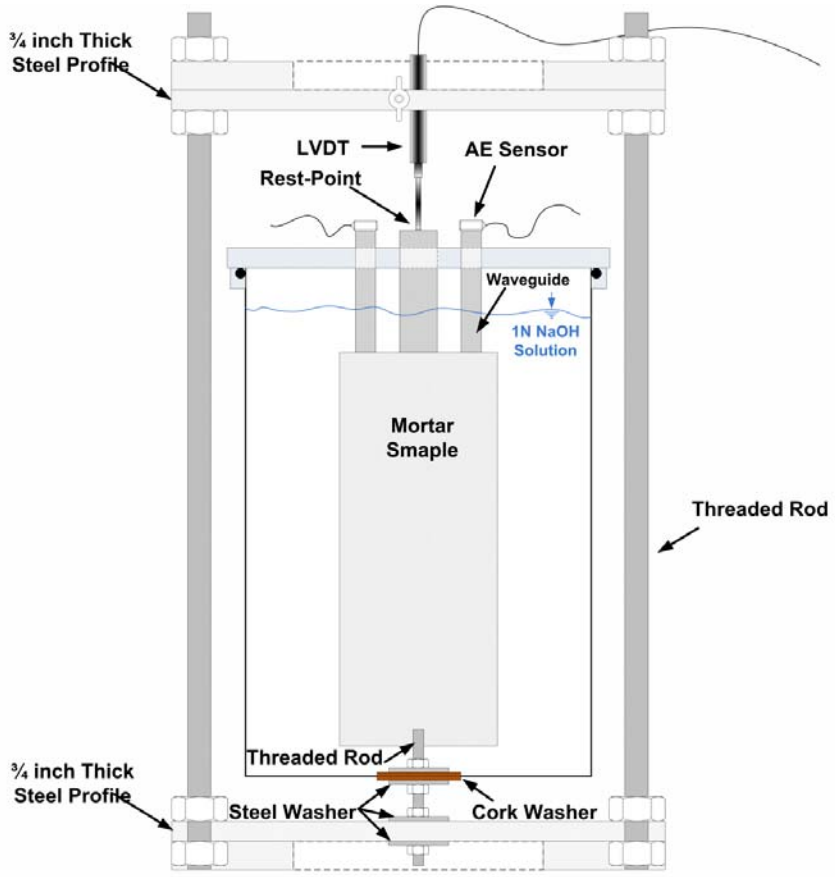

Figure 2: Schematic illustration of the experimental setup used for simultaneous length change and acoustic emission experiment

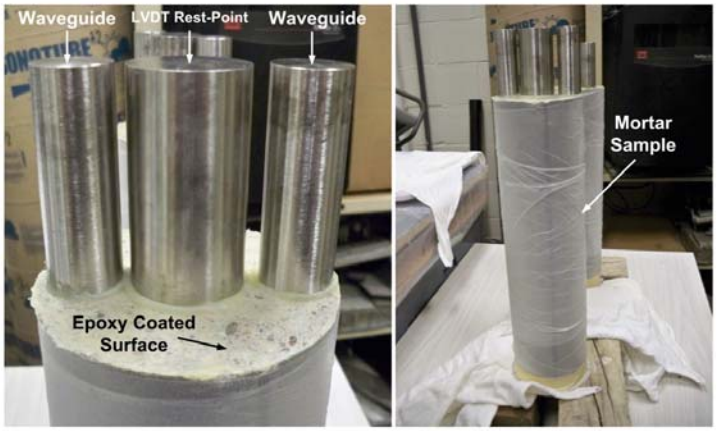

Figure 3: Photograph of the sample used for simultaneous length change and acoustic emission experiment: (a) waveguide and LVDT rest point, (b) mortar sample before submerging in solution

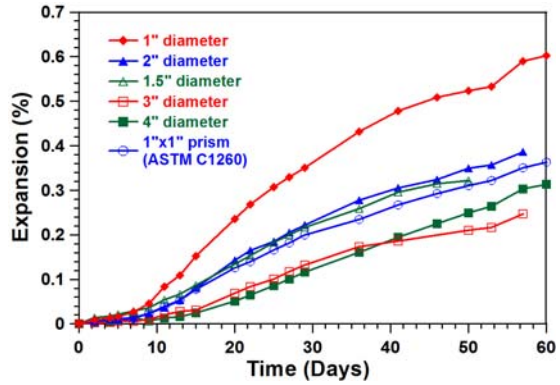

Figure 4: Expansion of cylindrical mortar specimens in 1N NaOH solution at 38±1°C (100±1.8°F)

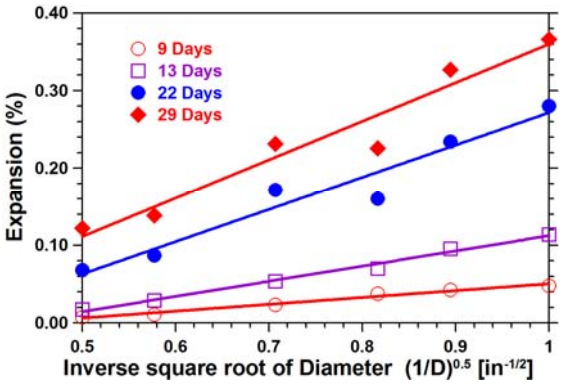

Figure 5: Expansion of cylindrical samples against the inverse square root of dimension

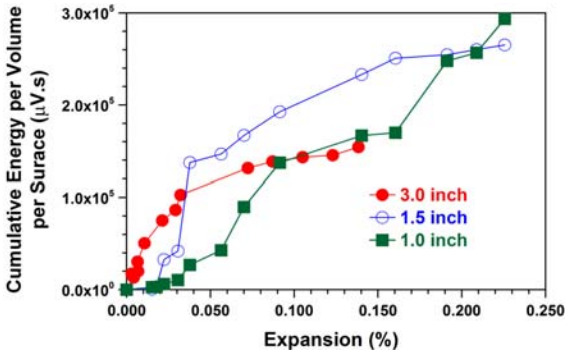

Figure 6: Normalized cumulative acoustic energy(per volume per surface) for different geometries

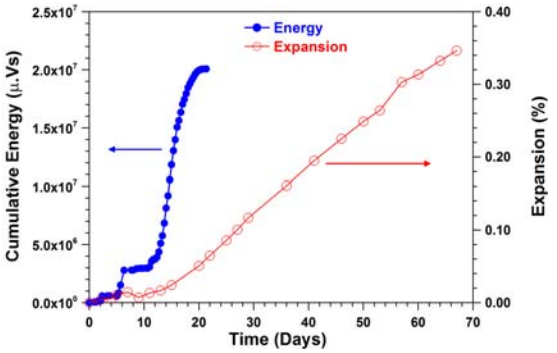

Figure 7: Cumulative acoustic energy and expansion of mortar specimen