Early-age detection of ASR in laboratory samples using ultrasonic coda wave monitoring

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Abstract

This paper presents preliminary results of a novel non-destructive evaluation (NDE) approach to monitor ASR in a laboratory setting: ultrasonic coda wave monitoring. The goal of the research is to provide early-age detection and distinction of ASR-affected concrete following the standard concrete prism test (CPT). The proposed monitoring approach has been found to be extremely sensitive to minute and slowly varying changes and may capture the onset of ASR at much earlier ages with a goal of providing a distinct improvement over the typical one or two-year time for the CPT. Two different exposure damage states were evaluated using concrete produced from essentially the same mixture design so as to not induce variables such as aggregate differences or different degrees of hydration. One fine aggregate known to be very highly reactive was used in concrete prepared according to the ASTM C1293 version of the CPT. Lithium nitrate was used to control the reaction to produce two damage states: no reactivity, and high reactivity. Companion samples were made for monitoring expansion to correlate to the results from the ultrasonic measurements. Test setups, proposed signal processing, as well as initial results for expansion and ultrasonic measurements are presented and discussed. Recommendations for further work are proposed.

***Keywords**: ASR; non-destructive evaluation; ultrasonic coda wave; monitoring; accelerated laboratory testing; early-age detection*

1. INTRODUCTION

1.1 Motivation

Among the current accelerated laboratory test methods used to assess aggregate reactivity and evaluate the effectiveness of mitigation measures, the concrete prism test – CPT (ASTM C1293) [1] has been considered to be the most reliable method. However, recent research showed that the CPT fails at evaluating the efficacy of mitigation measures for few mixtures correctly [2, 3, 4]. In addition, the limitations of the CPT include 1) long testing time (one year for evaluating aggregate reactivity and two years for evaluating the effectiveness of mitigation options), 2) alkali leaching from the specimens, and 3) incapability of real time monitoring. Therefore, there is a need to develop techniques that can overcome the limitations of the current methods to monitor ASR in real time and evaluate the efficacy of ASR mitigation options correctly with shorter testing time. This paper explores the use of ultrasonic coda wave monitoring as a promising solution to overcome some of the limitations of the CPT.

1.2 Background

Different non-destructive evaluation (NDE) methods have been proposed by researchers to monitor ASR progression in concrete in a laboratory setting. The simplest methods are based on basic properties of ultrasonic stress wave signals such as time of flight, p-wave velocity, or wave attenuation [5]. Rivard and Saint-Pierre measured p-wave velocities and estimated Young's modulus by resonant natural vibration frequencies and electrical resistivity [6]. They reported that electrical resistivity was not an effective measure. However, Young's modulus was effective for laboratory specimens but not the field, and ultrasonic p-velocity was effective for both laboratory and field specimens. Other studies have shown that nonlinear acoustic methods are more sensitive to ASR-induced changes in concrete. For example, Sargolzahi et al. tested and reported different NDE methods to detect ASR, reporting that ultrasonic p-wave velocity was only slightly affected by ASR but the nonlinear acoustic test was sensitive to ASR [7]. Furthermore, different nonlinear methods have been proposed to date such as nonlinear wave modulation spectroscopy (NWMS) and nonlinear impact resonance acoustic spectroscopy (NIRAS) [8, 9].

The problem with ultrasonic signals in concrete and heterogeneous materials comes from the fact that high frequency waves with wavelengths smaller than aggregates are strongly scattered in a concrete medium and low frequency wave properties are not sensitive to micro-cracks. Coda wave interferometry (CWI) has been shown to be an effective tool to detect changes in heterogeneous media [10]. Traditionally, the coherent portion such as the p-wave arrival had been examined in a signal. However, the later portions (or coda) of the signal encodes important information about scatterers inside the concrete [11]. Hafiz and Schumacher demonstrated that changes of the coda wave portion are directly correlated with stress changes in concrete and can be quantified using magnitude squared coherence [12].

1.3 Objective

The current ASTM C1293 standard method requires a long period of operation, which is typically one to two years [1]. Moreover, traditional ultrasonic wave properties such as arrival time are not sensitive to small internal changes in the concrete. The aim of this research is to provide early-age detection and distinction of ASR-affected concrete for the standard concrete prism test (CPT). Therefore, two mixtures with no reactivity and high reacitivty were monitored under controlled enviromental conditions including temperature and humitdity. Six samples were built in order to verify repeatibility of the process and companian prisms were built to test the standard expansion experiment.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

2.1 Materials and Mixtures

In this study, two concrete mixtures – Mix 1 and Mix 2, with and without lithium nitrate, respectively, were made according to ASTM C1293. A 100% lithium dosage was used in Mix 2 in order to mitigate ASR expansion. A high alkali cement with 0.96% Na_2O_e was used. The chemical composition of the cement is given in Table 2.1. A very highly reactive fine aggregate and a non-reactive calcium carbonate (high purity limestone) coarse aggregate was used. According to the standard, additional NaOH solution was added to the mixing water to increase the alkali content to 1.25% by mass of cement. Concrete prisms of dimensions 75 mm x 75 mm x 285 mm were cast for the expansion and ultrasonic monitoring. Concrete cylinders measuring 100 mm diameter x 200 mm length were cast for compressive strength.

Table 2.1: Chemical composition of the cement

Chemical composition (%)	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3	Na_2O_e
High alkali cement	0.15	1.40	5.26	20.51	4.28	1.23	64.20	2.09	0.96

Table 2.2 shows the mixture proportions and fresh properties of the concrete mixtures. Equal amounts of high-range water reducer (HRWR) were used in both mixtures to achieve good workability. Water content corrections were made when lithium nitrate (which is 70% water) and 50% w/w sodium hydroxide solution were added to the mixture to keep the water-to-cement ratio (of 0.42) the same for both of the mixtures.

Table 2.2: Mixture proportions and fresh properties of the concrete mixtures

Material	Mix 1	Mix 2
Cement (kg/m^3)	420.0	420.0
Water (kg/m^3)	176.4	176.4
Rock (OD) (kg/m^3)	1121.3	1121.3
Sand (OD) (kg/m^3)	677.3	677.3
HRWR (%bwc)	0.2	0.2
$LiNO_3$ (ml/g of alkali)	0.0	4.6
Slump (mm)	155	165
Unit weight (kg/m^3)	2409	2422

2.2 Experimental setups

The study was done in two separate university locations (~145 km apart), one having the ultrasonic monitoring setup and the other one an ASTM C1293 test setup. All prisms were cast in one location (C1293 location) and carefully transported to the ultrasonic monitoring location after one day of curing, which is when the measurements in both locations started.

2.2.1 Ultrasonic monitoring setup

Figure 2.1 (a) illustrates the ultrasonic monitoring setup. Two Panametrics V103 normal-wave transducers were attached to each of the six prisms in a pich-catch setup to transmit and receive ultrasonic signals (Figure 2.1 (b)). The transmitting transducer (T) received a 100 kHz sine pulse from a BK Precision 4053 arbitrary waveform generator, which was connected to a pulse amplifier (Trek 2100HF), every 500 s. The transducers were coupled to the underside of the prisms using hot-glue and secured with rubber bands. This was necessary to prevent transducer debonding due to the high humidity of the test environment. Two Elsys TraNET FE high speed data recorders, one a standalone (DAQ 1) and the other one a PCIe-based version (DAQ 2) were used simultaneously to collect the ultrasonic signals at a sampling rate of 2 MHz. Recording of the transient ultrasonic signals was triggered from the transmitted pulses to ensure consistent measurements.

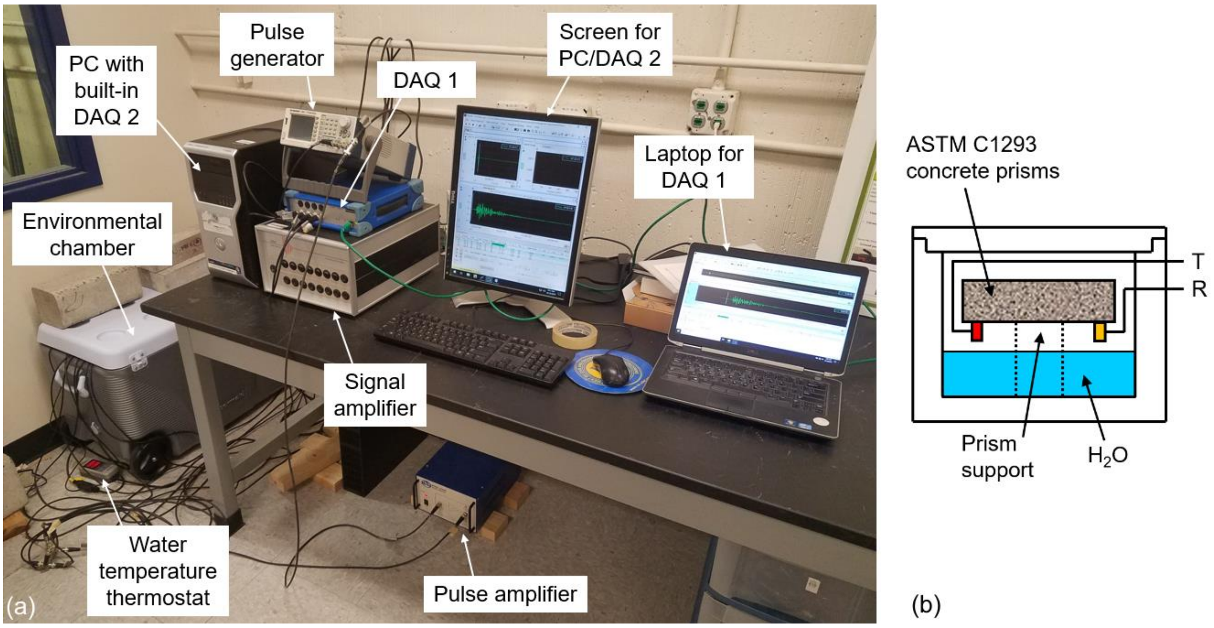

Figure 2.1: (a) Photo of experimental setup, (b) cross-section of environmental chamber holding six ASTM C1293 prisms. T and R represent transmitting and receiving transducers, respectively.

The environmental chamber holding the prisms was kept at a constant temperature by holding the water temperature at 40 °C employing a fish tank heater with a thermostat. The air temperature inside the chamber was recorded with a USB temperature logger. Figure 2.2 shows the temperature in the chamber for one week varying only slightly between 38.0 to 38.8 °C. This tight control was necessary because of the known sensitivity of ultrasonic coda wave measurements to temperature fluctuations [13]. Further, this falls within the temperature range allowed in ASTM C1293.

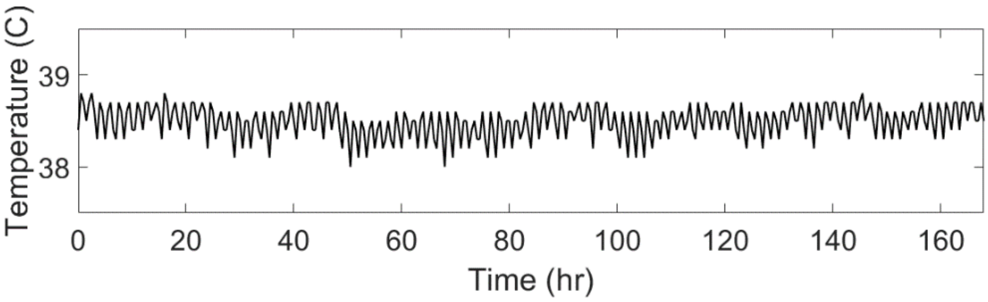

Figure 2.2: Sample one week measurement of air temperature in environmental chamber.

2.2.2 ASTM C1293 method

ASTM C1293 method or commonly referred to as the concrete prism test was used to monitor the expansion of the concrete prism specimens. ASTM C1293 was used as it is the most reliable standard test method available currently to evaluate aggregate reactivity and the efficiency of mitigation options to control ASR expansion. Three specimens per mixture were cast to monitor the expansions. The concrete prims were cured for 24 hours at 23 °C and then stored over water in sealed buckets at 38 °C. Expansion and mass measurements were taken at regular intervals as soon as they were removed from the 38 °C chamber rather than after cooling down the specimens to room temperature to minimize the differences in exposure conditions between the ASTM C1293 specimens and ultrasonic monitoring specimens. In addition, taking hot measurements, or in other words, not cooling down the prisms to room temperature before taking the expansion measurements would minimize the condensation and leaching from the specimens.

3. RESULTS AND DISCUSSION

Figure 3.1 shows sample ultrasonic signals that were recorded at 2, 28, and 56 days. It can be observed that the coherent portion (left inset), or p-wave arrival, does not change significantly over the duration of the experiment. The select coda wave portion (right inset), however, is affected notably over time, as can be observed by a consistent shift. Subsequently, the time shift of these two portions is discussed as potential indicators to distinguish specimens with and without ASR. Cross-correlation was used to compute the time shift by comparing the signal received at a specific time with a reference signal recorded at Day 2.

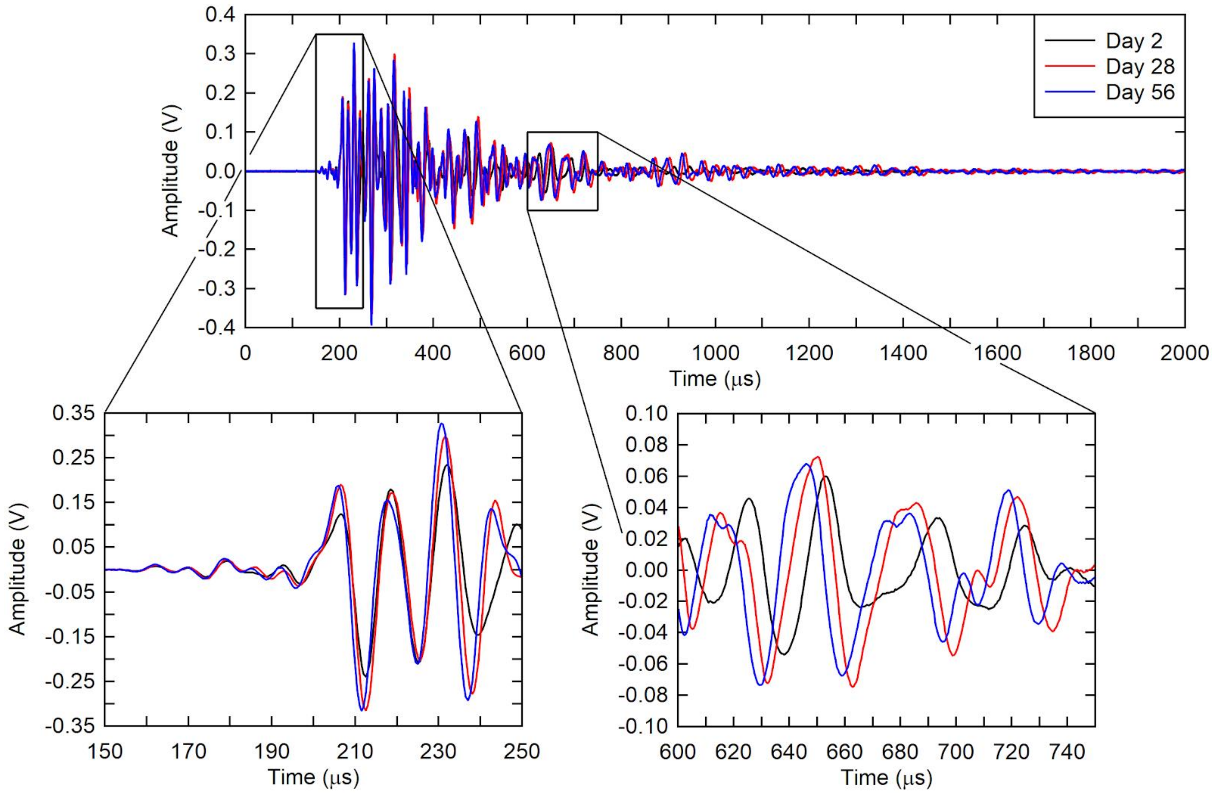

Figure 3.1: Sample ultrasonic signals recorded at 2, 28, and 56 days. Left and right insets highlight the coherent and coda wave portion, respectively, that was used for further analysis.

Figure 3.2 (a) shows the ASTM C1293 expansion results of the two mixtures with and without lithium nitrate. The red curve with square markers shows the expansion of the three Mix 1 – 0% Li specimens. The curve with triangle markers shows the expansion of the three Mix 2 – 100% Li specimens. Note that one of the specimens of Mix 2 behaved significantly different from the other two. It was observed that the average expansion of Mix 1 increased over time and crossed the expansion limit of 0.04% around 40 days. Whereas, the average expansion of Mix 2 relatively did not change after 20 days. This suggests that the 100% Li dosage in Mix 2 effectively controlled the ASR expansion during the test period.

Figure 3.2 (b) shows the p-wave arrival time shift, which was calculated by tracking the maximum amplitude of the first positive peak of the signal, corresponding to the p-wave. It can be observed that, while the curves do show a trend, the noise is too large to allow for extraction of useful information. The main reason, however, is that the early portions of the ultrasonic stress wave are not sensitive to changes due to ASR. On the other hand, the time shift of the coda wave portion shown in Figure 3.2 (c) is notably affected due to the multiple scattering that occurs inside the concrete. This shift was computed by cross-correlation of the coda wave signal between 600 and 750 μs (see right inset in Figure 3.1). It should be noted that the data from the third reactive prism are omitted from Figures 3.2 (b) and (c) since the sensor detached early on during the test due to coupling issues.

Two interesting features can be observed in Figure 3.2 (c): the first one from the beginning to Day 7, and the other one after Day 50. Figure 3.3 shows the first feature, which highlights the early age differences between reactive and non-reactive specimens. Because of the hardening process in concrete, which corresponds to in an increase in the modulus of elasticity, it is expected that stress wave velocity increases. This process can be observed as an increase in coda wave shift for the non-reactive specimens. However, for the reactive specimens, the trend is different and the coda wave shift is initially decreasing. Figure 3.3 shows the difference in the two mixtures from Day 1 to 7. In addition, Figure 3.4 shows two signal examples from Figure 3.3. Fig 3.4 (a) shows that for the non-reactive mixture, the coda wave is shifting to the left. Conversely, it is shifting to the right in the reactive mixture (Figure 3.4 (b)).

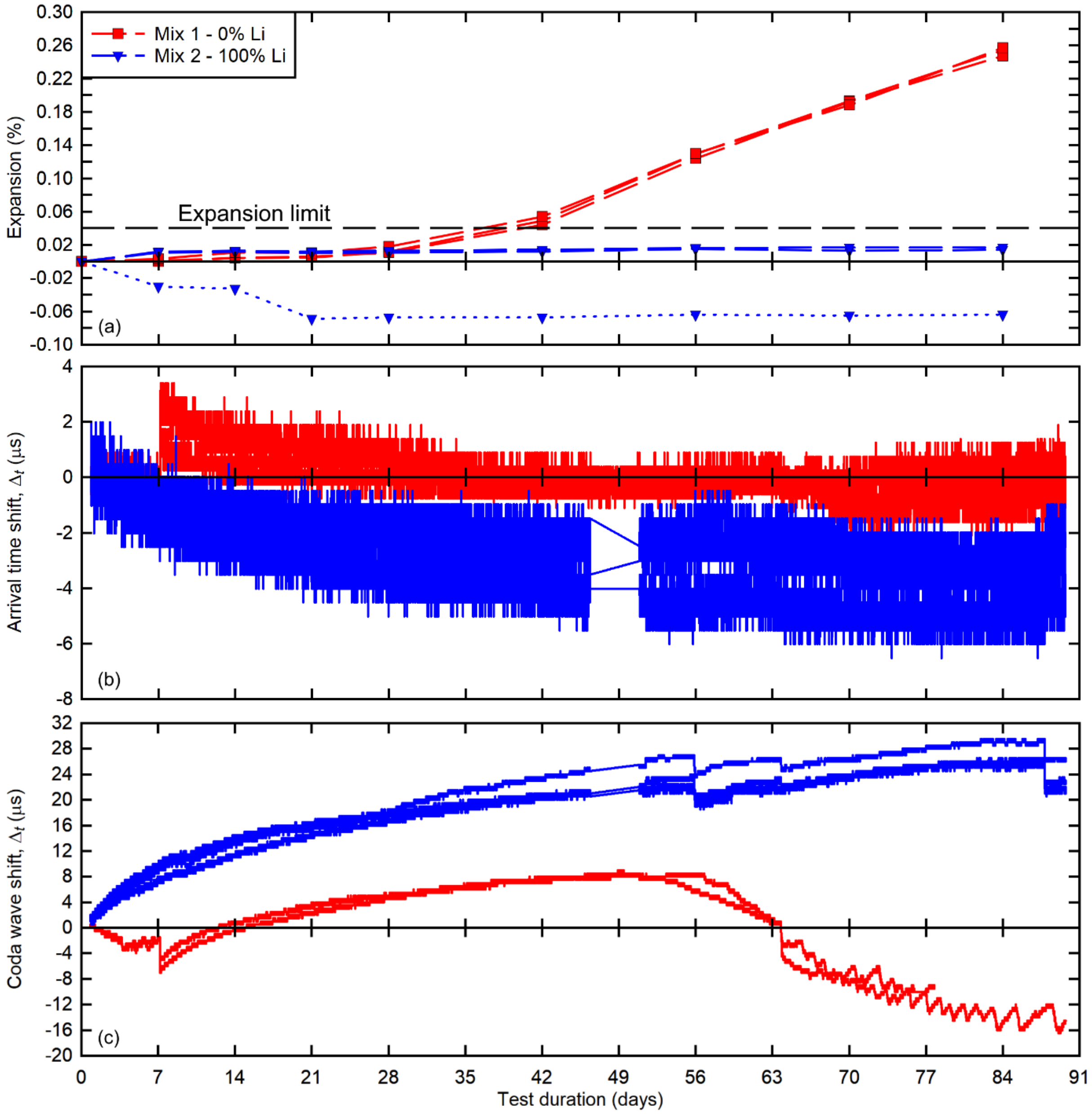

Figure 3.2: (a) Expansion results, (b) first-wave arrival time shift, and (c) coda wave time shift.

The other interesting feature in Figure 3.3 (c) occurs after Day 50, where the slope and pattern of the reactive and non-reactive specimens start to differ significantly. Examining the signals shows amplitude attenuation in the reactive specimens, which is when ASR is taking place. ASR gel expansion can result in micro-cracks inside the concrete, which is possibly the reason for the amplitude decrease in the signals.

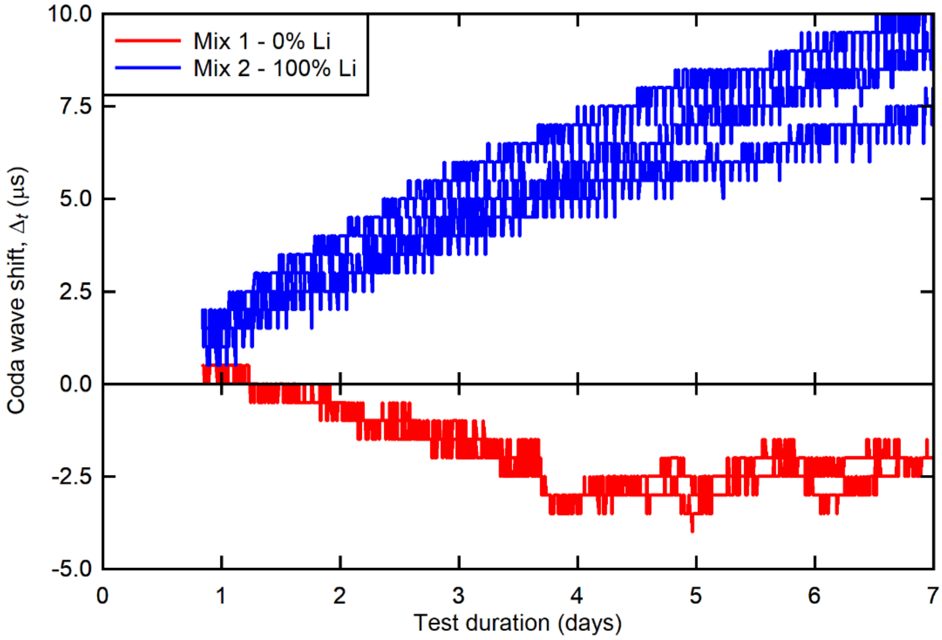

Figure 3.3: Coda wave time shift over the first seven days.

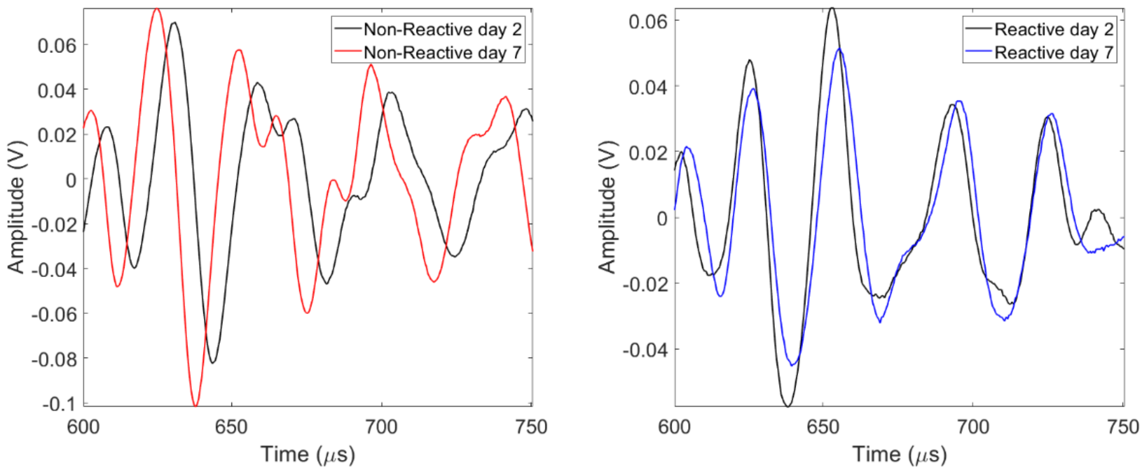

Figure 3.4: Sample coda wave windows before Day 7.

4. CONCLUSIONS AND FUTURE WORK

In this study, two concrete mixtures were investigated using ASTM C1293 in conjunction with ultrasonic coda wave form monitoring. One mixture was confirmed to be alkali-silica reactive and one incorporating 100% lithium nitrate and showing no deleterious expansion during the testing period according to both approaches. The conclusions and recommended future work from this study include:

- The drawback of ASTM C1293 is that it is a long test to run, one year for aggregate reactivity and two years for efficacy of mitigation measures. However, recent research has highlighted a lack of reliability in its ability to assess the efficacy of mitigation measures.
- The use of ultrasonic coda wave monitoring shows promise in detecting differences at a much earlier time period between ASR-affected and ASR-unaffected concrete specimens in the C1293 exposure environment.
- As more reliable laboratory test methods are sought including ultrasonic coda wave monitoring may allow for earlier distinction between effective and ineffective mitigation measures,

aggregate reactivity and for continuous monitoring where operator-induced error could be minimized.

- Further work on a larger suite of reactive and non-reactive aggregates as well as mitigation measures is needed to validate this promising approach.

5. ACKNOWLEDGMEMENT

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