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Effectiveness of Small Strain Shear Wave Velocity as a Property for Assessing Damage Associated with Alkali-Silica Reaction in Concrete

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Abstract

This research paper details the monitoring of expansion and shear wave velocity for fifteen concrete prisms cast in accordance with ASTM C1293 utilizing five mix designs with varying levels of ASR reactivity. Jobe sand and sodium hydroxide pellets were added in various quantities to increase the reactivity of the prisms. Strain measurements of the prisms were taken according to ASTM C129 and the shear wave velocity of the prisms was measured using ASTM C215. These measurements were taken weekly, then monthly for over a year. It was determined that shear wave velocity of the prisms decrease linearly as strain in the prisms increases with the relationship valid after the initial curing phase of the concrete (i.e., >56 days after casting). However, as cracks and other types of damage become more significant (i.e., individual cracking transitions to map cracking), the concrete can experience a significant loss in shear wave velocity without a proportionate increase in strain. Indicating shear wave velocity may provide a better estimate of concrete condition than strain measurements or visual inspection. For the determination of potentially deleteriously reactive concrete mixes, the shear wave velocity of prisms considered non-reactive (i.e., strain less than 0.04% in 1 year) had incremental increases in shear wave velocity over the 1 year period while prisms considered potentially deleteriously reactive had a decrease in shear wave velocity in the first 100 days. This indicates shear wave velocity may be useful as an alternative monitoring technique for determining potential deleteriously reactive concretes.

1. Introduction

Concrete can suffer deterioration in a number of ways, from freeze-thaw deterioration; to chemical attacks from acids, salts, or alkalis; or physical damage cause by fire, overloading, or impacts. Alkali-silica reaction (ASR) is a common chemical reaction in which alkalis (NaO, KO, and CaO) typically in cement react with silica acid (H4Si04) found in the concrete aggregates. The reaction occurs in the concrete pores where the cement paste interacts with the aggregates and creates an alkali-silica gel. The gel absorbs moisture in the concrete and causes expansion, leading to micro cracking that reduces the engineering properties of the concrete such as shear modulus, flexural strength and compressive strength. As damage due to ASR increase, the effects amplify until major, visible cracking occurs and strength properties decrease severely. ASR has become a major contributor to infrastructure problems, especially in areas with high temperature and relative humidity.

In any type of concrete deterioration, damage can occur before cracks appear on the surface of a concrete specimen; however, the current most common method for assessing damage is regular visual inspections. For structures suspected to be affected by ASR based from visual inspection may require invasive samples to be taken from the structure for further examination, causing even more damage. Still, there is no agreed-upon, standardized procedures for assessing and quantifying damage due to ASR. For these reasons, lots of recent research has been devoted to studying ASR and finding nondestructive testing (NDT) methods for assessing the condition of concrete.

Seismic methods are typically described as the most promising NDT method because their result (compression wave, unconstrained wave, or shear wave velocity) are directly related to the constrained, Young's, or shear modulus of the material (ASTM C215). Much of the research of NDTs has focused on longitudinal, P-waves along the surface of the concrete in question (Boyd & Ferraro 2005), such as ultrasonic pulse velocity (UPV), impact echo, dynamic modulus of elasticity (ASTM C215), and spectral analysis of surface waves (SASW). For a full review of NDT methods, see (Sanjeev, Bhadauria, & Akhtar 2013).

The research reported herein focuses on shear waves (also called S waves) in order to evaluate shear modulus as a viable engineering property capable of assessing concrete damage. In an elastic medium, transverse waves occur when it is subjected to periodic shear. The velocity of this shear wave is directly related to the shear modulus, a constant of the medium, and the density. Due to the marked difference between the amplitude of compression waves and surface waves, the leading edge of the surface waves can be identified on the waveform and their arrival time can be measured (Qixian & Bungey 1996). Unlike compression waves, shear waves are only transmitted in bulk matter (Sadri & Mirkhani 2009), and in the case of concrete, when voids form due to damage, the shear waves must travel around them. Therefore, the more damage sustained in the concrete, the farther the propagation path of the shear wave is at the same frequency, lowering the velocity. Here, we focus on the relationship between the shear wave velocity and concrete damage, in order to determine whether or not the loss in shear wave velocity is sensitive enough to detect the extent of deterioration.

In this laboratory experiment, ASR was used because it causes incremental damage to concrete over a relatively short period of time in the lab. The rate of expansion and final of expansion of concrete are dependent on the type of reactive aggregate, the amount present, and its particle distribution (Swamy & Al-Asali 1988). Concrete prisms with varying levels of reactivity were cast so that the shear wave velocities could be measured as the strain values increases. A relationship is established between shear wave velocity and longitudinal strain in these concrete prisms and the behavior of the concrete prisms in terms of shear wave velocity and strain are discussed.

2. Test Methods

In order to establish a relationship between shear wave velocity (Vs) and concrete deterioration, concrete prisms with varying degrees of ASR reactivity were cast in the lab. The expansion and Vs were measured at regular intervals to establish a correlation between Vs and longitudinal strain.

2.1.1 Casting and Curing

Fifteen (15) concrete prism were cast from the 24th of June, 2015 to the 30th of July, 2015 in accordance with ASTM C1293 and C215 by Ben Davis (Davis 2016). Each prism was cast with dimensions of 7.6 cm x 7.6 cm x 27.9 cm. using Humboldt MFG H3254 molds (shown in Figure 2.1a). The molds had a threaded hole on either end which allowed for small metal studs to be embedded in the prisms which were used to as a reference point for strain measurements. Images of the cast prisms with studs are depicted in Figures 2-1b.

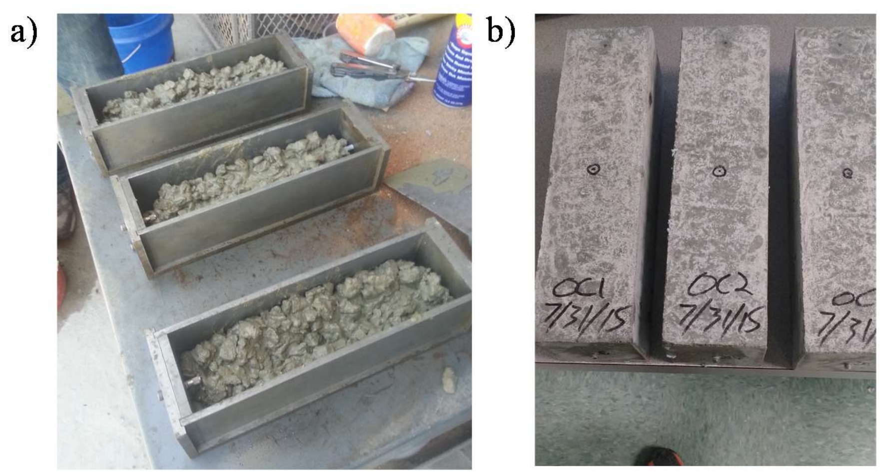

Figure 2-1: a) Casting of prisms and b) cured prisms.

Once the prisms were cast, they were cured in a 23.5°C curing room for 24 hours then demolded. After demolding, the prisms were placed in a five gallon buckets detailed in Figure 2-2. The bucket was then placed in a hot water bath (37.8°C). The hot water bath consisted of a

0.61m x 1.82m x0.61m (0.64m^3) galvanized metal stock tank, temperature variable switch with plug-in, immersion water heater, 0.5 $\frac{m^3}{hr}$ pump, and foam lid. The temperature variable switch and heater kept the water between 36.7 and 38.9°C. The water heater was suspended in the water by a 10cm x 10cm x 7.5cm cube of blue insulation foam. A picture of the water bath is shown in Figure 2-3. On June 3rd, 2016, salt was added to the warm water bath to increase the reaction rate in the prisms.

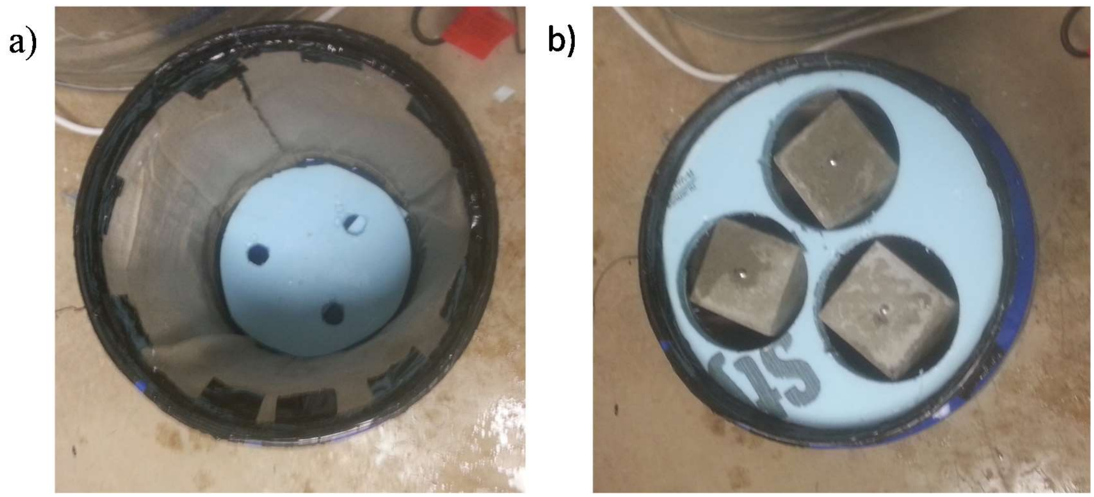

Figure 2-2: Five gallon bucket for accelerated ASR prisms.

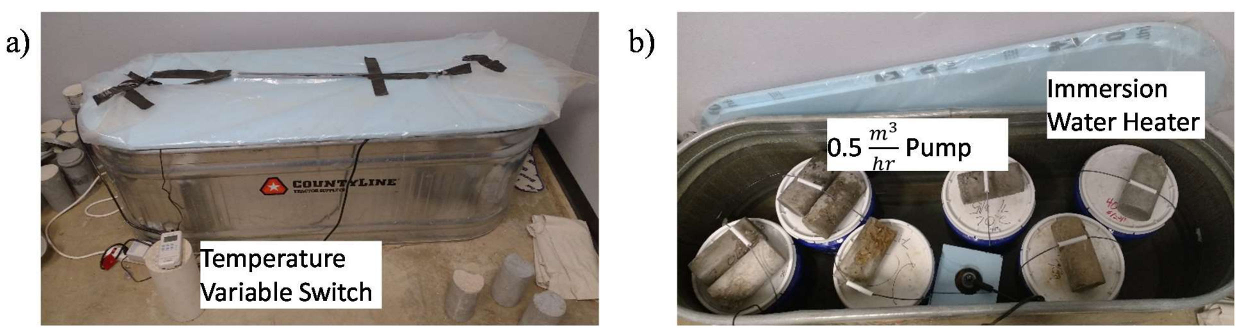

Figure 2-3: Water bath for accelerated ASR prisms illustrating a) temperature variable switch and b) the immersion heater and 0.5 m^3/hr. pump.

2.1.2 Mix Designs

Five different mix designs were used to create the 15 prisms in order to produce concrete specimen with varying ranges of ASR reactivity. The mix designs are detailed in Table 2-1. Two fine aggregates were utilized for the mix designs of the concrete prism: Jobe sand and Van Buren sand. Both aggregates have been identified as potentially deleteriously reactive with Jobe sand having the higher reaction potential than the Van Buren sand while the cement used had an alkali content of 0.9% (Phillips et al. 2015). For the 15 prisms cast, three prism were casts using each mix design. The mix designs varied primarily by changing the amount of Job sand and sodium hydroxide (NaOH) pellets used in the mix. For mixes which included sodium hydroxide pellets, the alkali content was raised from 0.9% to 1.25%, ensuring an excess of alkalis available to react with silica acid in the Jobe and Van Buren sand. Mix designs with sodium hydroxide pellets are denoted with an "R" and the designs without, "C." Our base group, denoted as "0C," had only Van Buren sand, making it the least reactive mix design. Mix designs "20C" and "20R" had a Van Buren to Jobe sand ratio of 4:1, while mix designs "40C" and "40R" used a Van Buren to Jobe sand ratio of 3:2. A granite aggregate was used due to convenience and lack of reactivity.

Table 2-1: Mix Designs

Material	0C	20C	20R	40C	40R
Cement	6.56 lb	6.56 lb	6.56 lb	6.56 lb	6.56 lb
Coarse Aggregate	16.50 lb	16.50 lb	16.50 lb	16.50 lb	16.50 lb
Jobe Sand	0.00 lb	2.13 lb	2.13 lb	4.37 lb	4.37 lb
Van Buren Sand	10.67 lb	8.54 lb	8.54 lb	6.40 lb	6.40 lb
Water	3.06 lb	3.06 lb	3.06 lb	3.06 lb	3.06 lb
NaOH	0.00 g	0.00 g	13.82 g	0.00 g	13.82 g

2.1.3 Expansion and Shear Wave Velocity

After the first and third days, expansion measurements for the prisms were made weekly and then monthly using a strain gauge in accordance with ASTM C129. An example of the strain gauge used to measure expansion is presented in Figure 2-. After removal from the curing tank, each prism was toweled off and allowed to air dry for a minimum of one hour before strain and shear wave velocity measurements were taken. After drying, the samples were measured with a digital caliper to one-thousandth of an inch and weighed to one-tenth of a gram.

The shear wave velocity of each prism was determined by following the procedures outlined in ASTM C215. The ASTM specifies how to measure the fundamental transverse, longitudinal, and torsional frequencies of a concrete prism. For this study, the torsional frequency was of interest because it is a function of the material's shear wave velocity.

The test is performed by supporting the prism at its longitudinal midpoint by a foam strip. An accelerometer is then placed 1.3 cm from the top surface and 6.6 cm from one end. The accelerometers had a resonant frequency of 60 kHz and a sensitivity of 100 mv/g. The accelerometer was attached to the concrete prism using PCB accelerometer wax. The prism is then struck with an instrumented 230 gram PCB hammer, 1.3 cm from the bottom and 3.6 cm from the opposite end. Five averages were taken for each prism. A schematic of the accelerometer placement and strike point is presented in Figure 2-.

Figure 2-4: ASR prism being tested for expansion.

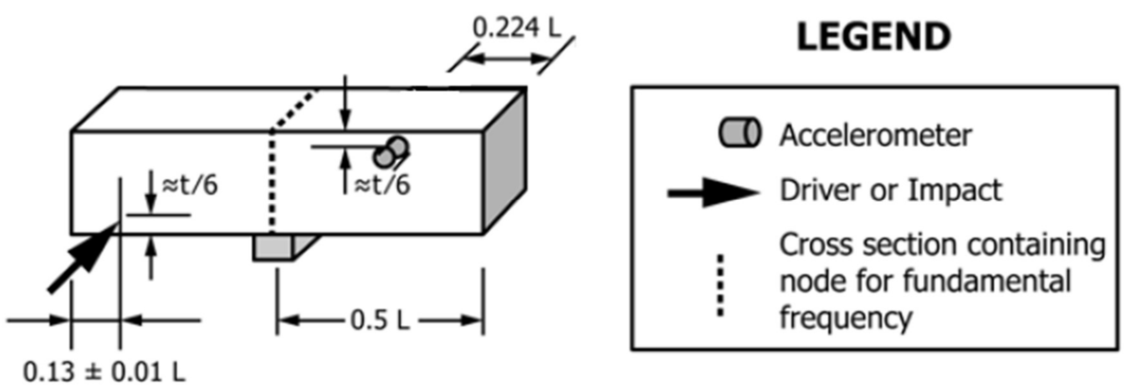

Figure 2-5: Schematic of accelerometer placement and strike point (ASTM C215).

The data from the accelerometer was recorded using a Data Physics Quattro. The Quattro has four input channels, two output channels, 240 kHz sampling rate, and a dynamic range of over 120 dB. A Nyquist frequency of 80 kHz and a total of 12800 frequency domain points were used, which resulted in a frequency resolution of 6.25 Hz. An example output of the average auto power spectrum is presented in Figure 2-6. The figure is used to pick the peak frequency. The test was conducted at the same time as the expansion testing. After testing was completed, each specimen was weighed and measured.

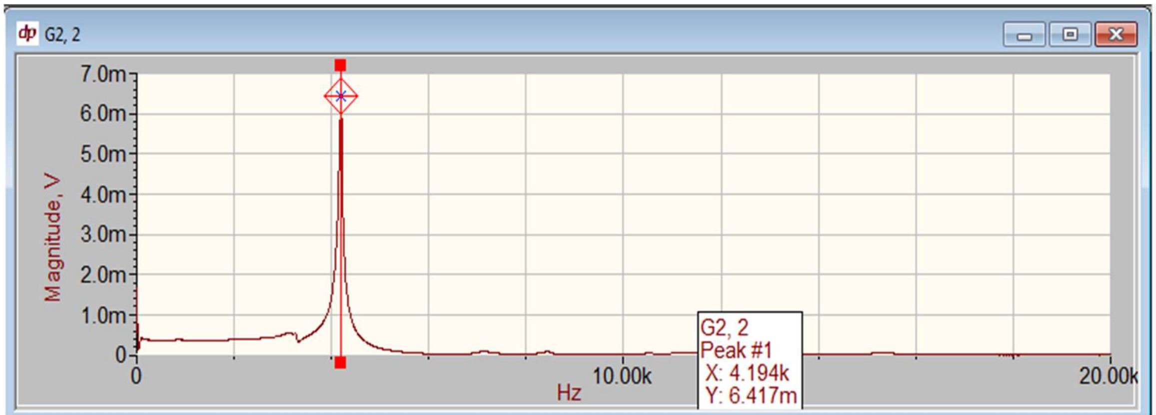

Figure 2-1. Example output from SignalCalc 240 with the fundamental frequency highlighted.

3. Results and Discussions

In Figure 3-1, the strain and the shear wave velocities of the averages of each mix design are shown versus time. In order to increase the rate of reaction of ASR in the specimens, salt was added to the warm bath on May 3rd, 2016, between 300 and 330 days after the prisms were cast. The time of this addition is depicted as the area between the dashed lines on the graph. Comparing the strain and Vs, there is a strong inverse relationship between strain and Vs. Using strain as a measure of material damage, it is clear that as damage increases, Vs decreases. Comparing the 20R and 40C prisms more closely, at the 200 day mark the Vs of the prisms cross over one another, the strain results seem to have the same cross over point at 200 days. This very well correlated behavior of stain and Vs can be observed at a number of times in the dataset indicating strain is very well correlated with Vs for these prisms. Comparing the results before the salt is added (time less than 300 days), the samples with the highest Vs have the lowest measured strain. Conversely, the highest strain samples have the lowest Vs. It is also evident that the salt addition had the desired effect; as the rate of ASR increases, the strain values increased and the shear wave velocities dropped significantly. Comparing the rate of strain buildup and loss in Vs of the prisms, the least reactive prisms took longer to deteriorate with the OC prisms taking over 400 days to reach 0.1% strain (likely only reaching this range because of the addition of the salt). Conversely, the most reactive specimens reached the highest strain values and had a faster rate of reaction. For example, the 40R samples reached strain values of 0.7% by the end of the experiment.

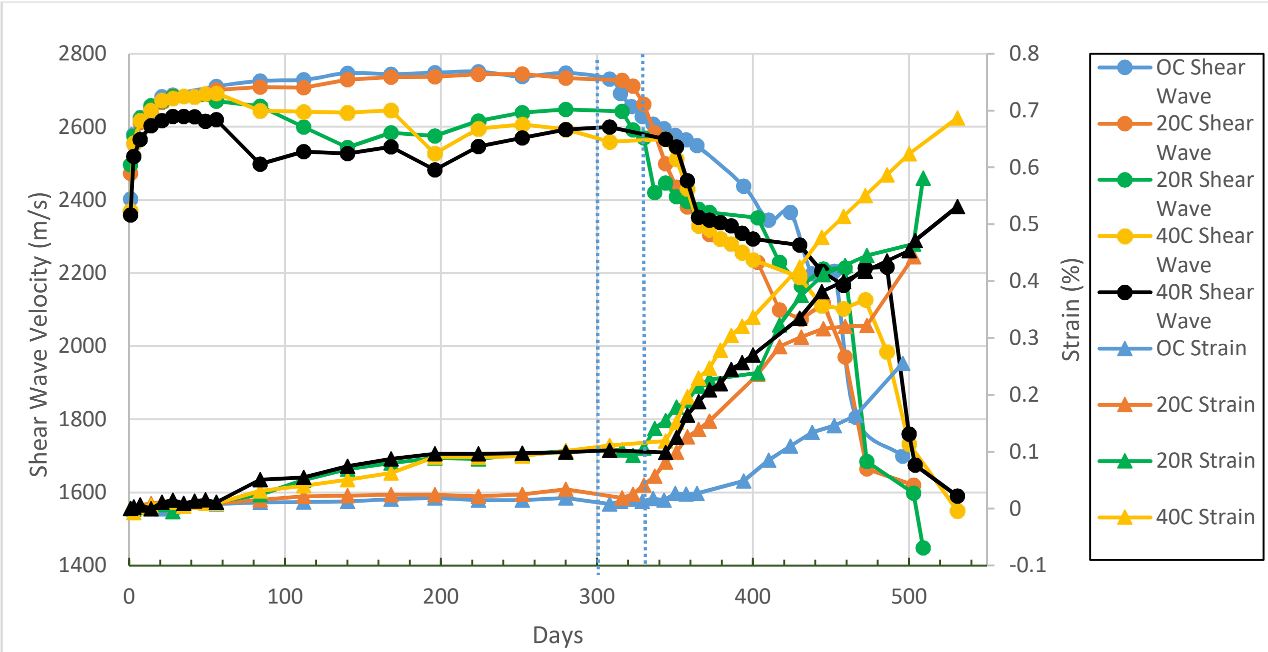

Figure 3-1: Shear wave velocity measured for each prism based on the number of days since casting (left axis) and longitudinal strain of prisms based on number of days since casting (right axis). Salt was added to the bath between 300-330 days from when the prisms where cast (depicted by the blue dashed lines).

In Table 3-1, the maximum shear wave velocity of the average of the three cylinders for each mix design is shown. The table also highlights the strain values when the maximum velocity was reached and how many days it took to be achieved. Generally, the least reactive prisms had slightly higher maximum shear wave velocities; however, there is only approximately a 4.5% difference among all of the different mix designs. More significantly, the prisms most susceptible to ASR reactions reached their maximum shear wave velocities dramatically sooner than the lesser reactive ones. As the concrete hardens during the curing process, it has been shown that stress wave velocities increase with time (Boyd & Ferraro 2005). Since velocities increase during the curing process, it can be inferred that either high levels of ASR can interrupt the curing process in concrete, or the rate of ASR in particularly reactive samples is higher than the curing rate in the later stages of the curing process such that shear wave velocity drops more due to ASR than it increases due to curing.

Table 3-1 Maximum average shear wave velocity from each set of three prisms

	Maximum Shear Wave Velocity	Strain at Max Velocity	Days until Max Velocity Reached
0C	2751.14	0.015	224
20C	2744.33	0.025	252
20R	2670.05	0.012	56
40C	2692.09	0.009	56
40R	2628.52	0.015	28

To more clearly show the relationship between Vs and strain, the two values are plotting together in Figure 3-2. Again, the values presented are the average of the three prism for each mix design. At strain values greater than 0.1% (i.e., once the relationship between curing in the concrete and strain increase due to ASR has stabilized), there is a distinct correlation between shear wave velocity and expansion. Before this point the rate of reaction and strength gain in the prisms makes the data more variable at lower strain values. The negative trend in Figure 3-2 is strong enough that given a strain value, the Vs can be estimated, and vice-versa. The sudden drops in shear wave velocities in Figure 3-2 are likely due to a change in the type of damage in the concrete specimens. Once microcracking upgrades to "map cracking" or when individual cracks connect together to form large cracks across the entire prism, there is a significant drop in Vs. However, a corresponding large increase in strain is not observed. This indicates that Vs is a better measure of damage or condition of concrete than longitudinal strain. Comparing the time and strain when this occurs, this sudden loss of Vs does not seem to be correlated well with strain, but better correlated with time since the salt was added to the bath with all prisms failing between 445-486 days (142-156 days after the salts were added). This increased reaction rate likely caused a significant increase in damage to each set of prisms regardless of the original reactivity of each prism.

In Figure 3-3, the outlying data in Figure 3-2 has been removed (i.e., big drops in shear wave velocity and unstable Vs/strain combinations before a stable relationship had formed). A linear trend line is used to develop a relationship between strain and Vs with a R^2 value of 0.80. To normalize the Vs values for each prism set, which is necessary to create an overall relationship which can be used for multiple mix designs with different maximum Vs values, the Vs values measured for each prism are divided by the Vs at 56 days. This normalized relationship between Vs and strain is provided in Equation 3-1.

$$Vs = -0.2854\ \varepsilon + 1.0146 \qquad \text{Equation 1}$$

Where Vs is the shear wave velocity, and ε is strain. This correlation is valid at strains past the initial curing point where the Vs of the concrete starts to decrease, but also assumes that a significant drop in shear wave velocity due to major damage has not yet occurred.

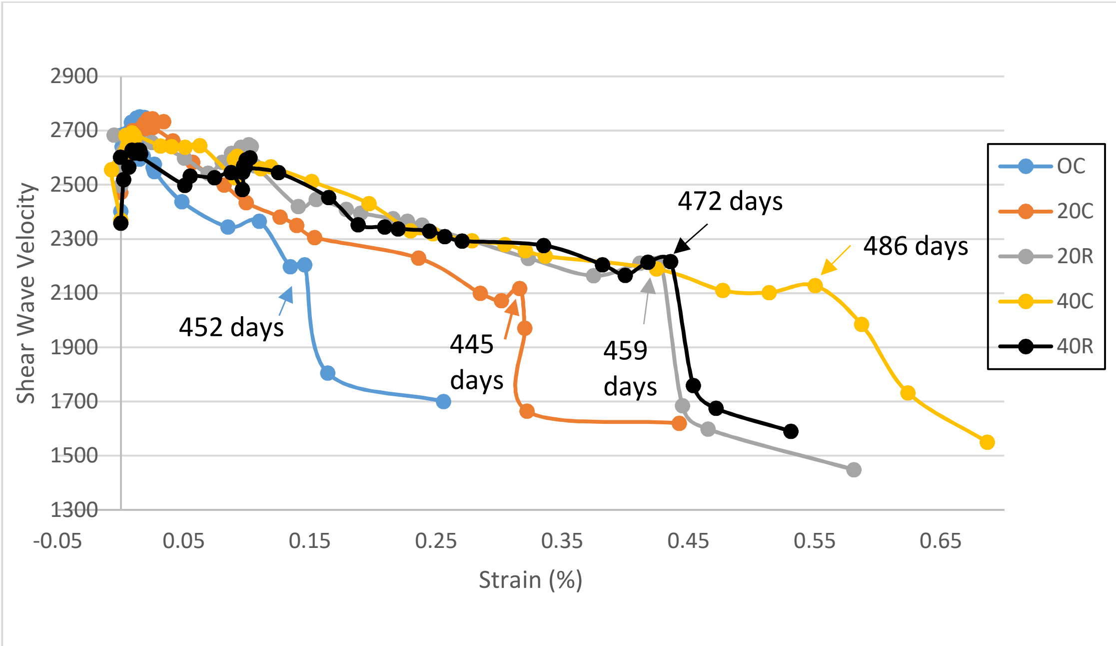

Figure 3-2: Shear wave velocity and strain results from concrete prisms (average of the three prisms is shown).

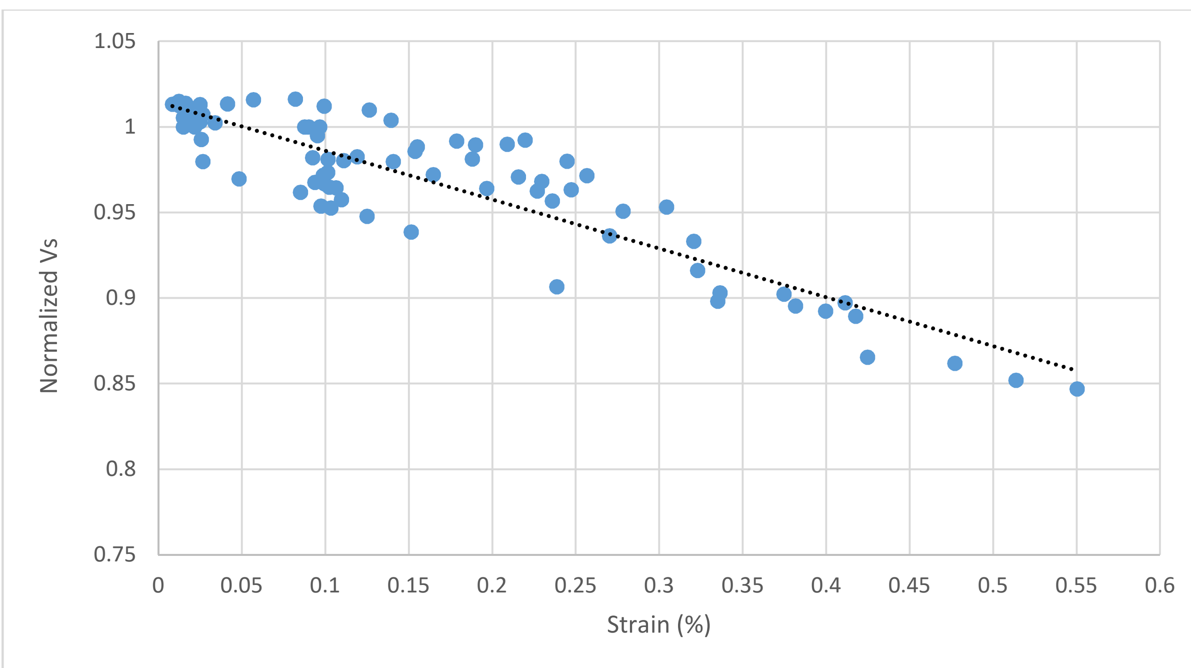

Figure 3-3: Correlation between Shear Wave Velocity and Strain

In Figure 3-4 and 3-5, the Vs of the prisms at strains less than 0.1% and time before the salts were added are examined. All data after the salts were added to the bath has been removed from the Figure 3-4 because these measurements are believed to represent atypical ASR behavior for the concrete specimen. Overall, the prims generally have an increase in Vs and an increase in strain especially for the least reactive prisms (0C and 20C). However, there is some variability in the relationship between Vs and strain especially at lower strain values. As previously discussed, this increase in Vs and strain together is likely due to ASR related damage lowering the Vs while the curing process simultaneously increases Vs, which in the early stages of the curing process result in both increases in strain and Vs. For the least reactive prisms (0C and 20C), this increase in Vs is observed for almost the entire recording period before salts were added, while for the reactive prisms (20R, 40C, and 40R), a decrease in Vs is observed at relatively low strains and relatively short time periods (less than 100 days). Since the reactive prisms exceed 0.04% strain before one year, they would be considered "potentially deleteriously reactive" according to ASTM C1293. Since a loss in shear wave velocity is also observed in these prisms around the 0.04% strain range, it can be said that a decrease in Vs in prisms within 1 year of casting would also indicate the prisms are potentially deleteriously reactive. Moreover, the decrease in Vs for these reactive prisms often occurs before the 0.04% strain mark, which means a loss in Vs might be an earlier indicator that the prisms would be potentially deleteriously reactive. Overall, if a specimen records an increase in Vs for an entire year, then it mostly likely would have strains less than 0.04% and would not be potentially deleteriously reactive. However, if the structure in question begins to lose Vs within a year, then it is most likely that it will cross the potentially deleteriously reactive threshold and have problems with damage due to ASR.

In Figure 3-5, the behavior of Vs and strain in the prism during the first 300 days, before any salt is added, is observed with respect to time. This figure accentuates the difference in the more reactive prisms (20R, 40C, and 40R) with the less reactive prisms (0C and 20C). All three of the more reactive prisms achieved strain levels of at least 0.1% in the first 300 days and experienced a loss in Vs. Conversely, 0C and 20C stayed below the potentially deleteriously reactive threshold and had increasing Vs for the first 300 days well above the reactive mix designs. This reiterates the conclusion that early monitoring of Vs in a concrete structure can be used to detect if damage due to ASR will be a problem for the structure.

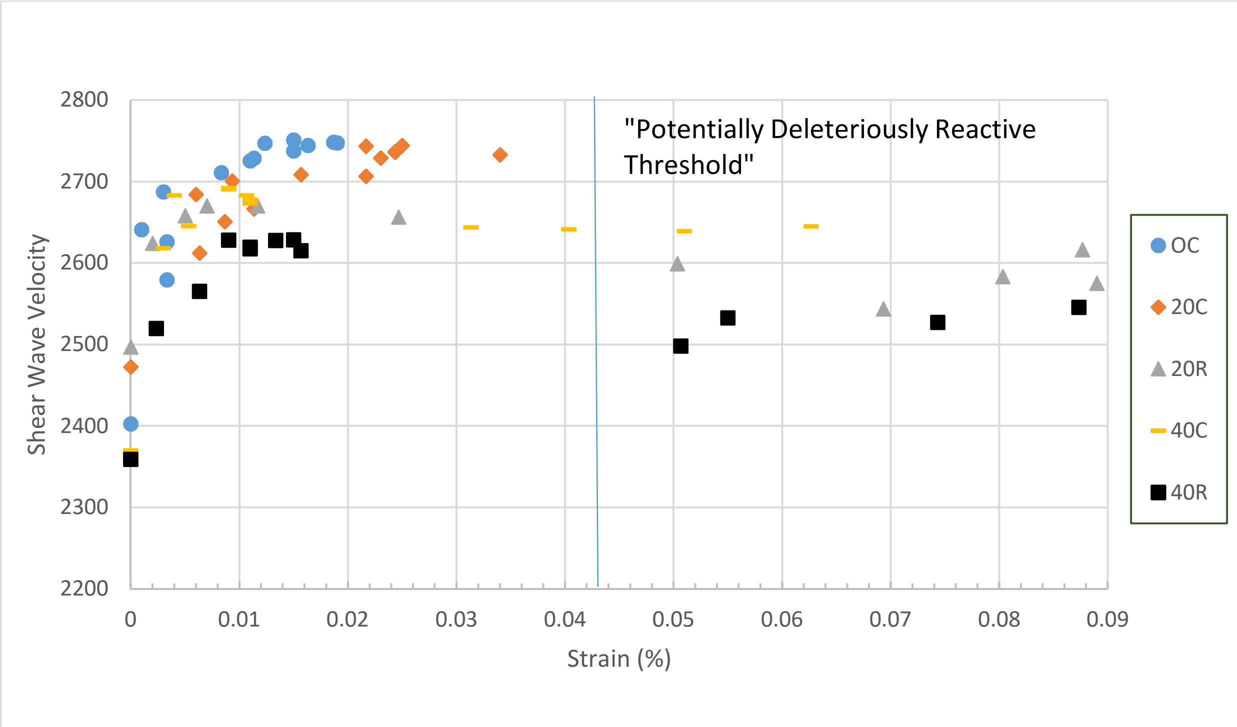

Figure 3-4: Shear Wave Velocity vs Strain at Strain Values Less Than 0.09% (only measurements made before the addition of salt are shown)

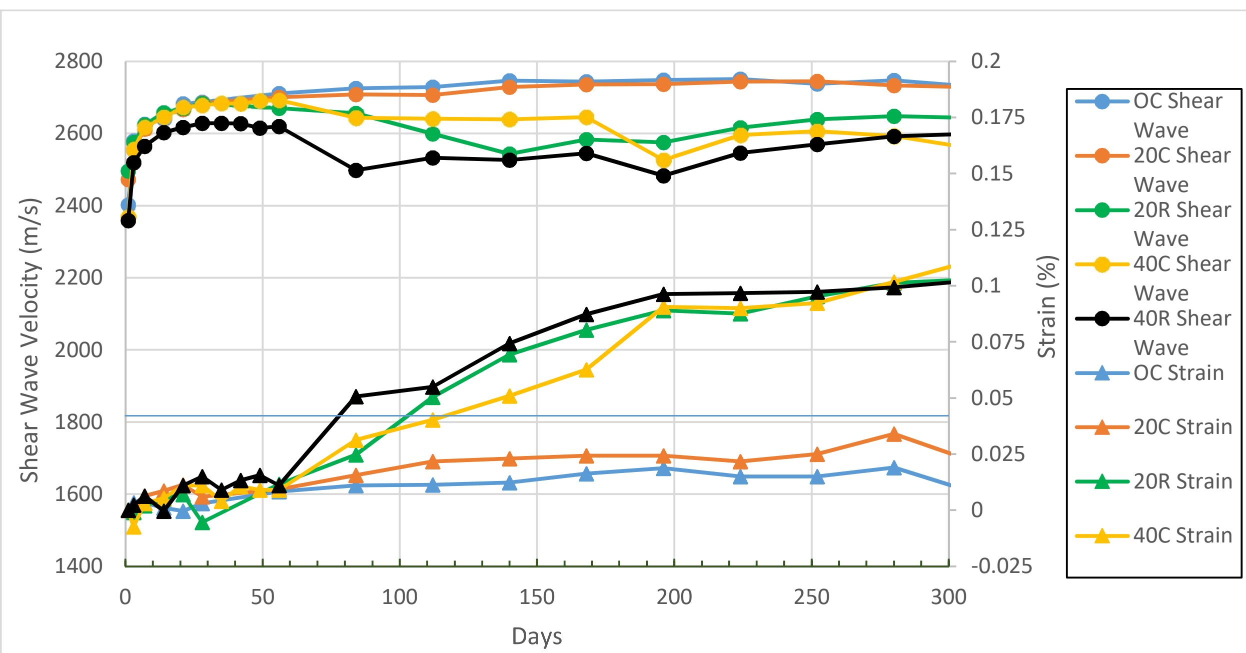

Figure 3-5: Shear wave velocity measured for each mix design based on the number of days since casting (left axis) and longitudinal strain of prisms based on number of days since casting (right axis) until salt was added to the curing tank

4. Conclusion

The results of the study indicate at strains beyond the initial curing period (i.e., > 56 days after casting) when Vs has begun to decrease, there is a strong linear correlation between strains in concrete and Vs. This indicates that shear wave velocity can be an effective property to categorize the level of concrete damage both of concrete prisms and in-service concrete structures. However, there is not a strong relationship between strain and Vs during the initial curing process likely due to the complex interaction of curing and ASR deterioration. Although, there is not a strong correlation between Vs and strain during the early stages of curing, a loss in Vs during the first year can be a strong indicator that a particular prism or concrete structure will be potentially deleteriously reactive. Moreover, an observed loss in Vs may occur at an earlier time than the traditional 0.04% strain mark is reached possibly confirming potentially deleteriously reactivity at an earlier time period reducing the time needed for lab testing. Finally for concrete prisms in this study, a large drop in Vs was observed in all the prisms following the aggressive ASR reaction after the addition of salt. Vs was better able to describe this increase in damage of the concrete prisms than strain measurements. Therefore, if a more quantitative understanding of the concrete condition is desired, Vs is likely more appropriate than traditional visual or strain measurements.

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