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Young's Modulus as a Measurement to Estimate Damage Related with Alkali-Silica Reaction in Concrete.

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Abstract

The main purpose of this research is to compare two nondestructive methods to assess Alkali-Silica reaction (ASR) in concrete. Fifteen concrete prisms were cast using aggregates with different Alkali-Silica reactivity such as Jobe sand and Van Buren sand. The change in strain, shear wave velocity and Young's modulus were determined according to ASTM C129 and ASTM C215, respectively. This data was collected by Dillon K Self, who determined that the shear wave velocity and strain are inversely proportional. However, when single cracking in the concrete specimen transition to map cracking, the shear wave velocity dropped significantly, whereas the strain value does not. Thus, the shear wave velocity is more sensitive than strain measurements to determine the damage caused by (ASR) in concrete. The Young's modulus data was analyzed and compared to the results obtained from Self's experiments using shear wave velocity. Young's Modulus of the concrete prisms typically follows the same trends as shear wave velocity with strain increasing the Young's modulus decreases. The percent decrease in Young's modulus is similar to the percent decrease in shear modulus, and both occur at nearly the same rate and specimen age. Thus, Young's modulus and shear modulus provide a good estimate to assess concrete conditions.

1. Introduction

Alkali-Silica reaction (ASR) is a chemical reaction that occurs when the alkalis from the cement paste interact with the silica acid from the aggregates used to make concrete. This chemical interaction generates an alkali-silica gel, which expands in the presence of moisture leading to internal damage in concrete. Previously, ASR damage assessment was based on visual inspection and surface cracking. These *in situ* tests provided the general condition of the structure, but it is usually based on subjective opinions and relies heavily on the experience of the inspector rather than quantitative measurements (Sargolzaei, 2010).

Once the structure is classified as potentially affected by ASR, concrete coring occurs, and samples are taken from the structure. These samples are used to evaluate specific properties of the concrete such as strength. However, this destructive method is time consuming and labor intensive (Lee, 2017). Nondestructive methods (NDT) have become more appealing to assess ASR because they are less labor intensive and less subjective. One of the most auspicious NDT methods are seismic methods. They are stress waves measurements such as shear wave velocity and compression wave velocity, which can be used to estimate Young's modulus or shear modulus of the concrete specimen (ASTM C215).

Young's modulus and shear modulus are material properties used to assess concrete condition. Shear modulus is the result of shear wave velocity squared times mass density. Since velocity can be defined as distance travelled divided by time, the shear wave velocity will decrease as travel time increases. Thus, if the concrete specimen has voids, the shear wave velocity will have to go around the voids, and it will take longer for the wave to travel from one end to the other end of the concrete specimen. This is due to the fact that shear wave velocity can only travel in bulk matter. In the same way, the transversal vibration frequency is used to determine the Young's modulus. Frequency can be defined as 1 divided by time (period), so as time increases the frequency and Young's modulus decrease.

Multiple research has been focused on comparing the effectiveness of different NDT methods, such as ultrasonic pulse velocity, dynamic modulus of elasticity, nonlinear frequency shift, harmonic generation and petrographic examination (Sargolzaei 2010). However, seismic methods such as ultrasonic pulse velocity have not been the main focus of available literature. Thus, this paper will be focused on comparing the effectiveness of two parameters obtained

using seismic methods, Young's modulus and shear wave velocity as well as the change in strain.

In this study, 15 concrete prisms with different ASR reactivity levels were used. The Young's modulus and the strain values were estimated using ASTM C215 and ASTM C129 and compared to the shear wave velocity and shear modulus to determine which method is more sensitive to assess damage due to ASR.

2. Test Methods:

Fifteen concrete prisms with the dimensions of 7.6 cm x 7.6 cm x 27.9 cm were cast following ASTM C1293 and C215 standards. When the concrete prisms were cast, a small piece of metal was embedded in the concrete prisms which was used as a reference point to measure the change in strain (Figure 2.1). These prisms were cured at 23.5°C and then placed in a water bath at 37.8°C. The water bath consisted of a metal tank with the dimensions of 0.61m x 1.82m x 0.61m. The prisms were placed in 5-gallon buckets before they were placed in water bath. Between 300 and 330 days after the prisms were cast salts were added to accelerate the reaction rate.



Figure 2.1. Prisms which were used in this research.

Five different mixes were used to create concrete prisms with different Alkali-Silica reactivity. Figure 2.1 shows the different mixes used. Three different prisms were made from each mix and then averaged.

Table 2. 1. Mix Design

Material	0C	20 C	20 R	40 C	40 R
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

The letter R in Table 2.1 was used to denote the mixes with Sodium hydroxide (NaOH) added and C denotes the ones that did not have NaOH added. The numbers were used to denote different ratios between the two types of sand used, 0 was our control group, 20 had a ratio of 4:1 Van Buren sand to Jobe sand and 40 had a ratio of 3:2 Van Buren sand to Jobe sand. Jobe sand is more reactive than Van Buren sand. Additionally, the cement used had 0.9% alkali content, but with the addition of NaOH the alkali percent increased from 0.9% to 1.25%. NaOH was used to increase the rate of the ASR.

Shear Wave Velocity, Young's Modulus and Expansion

ASTM C129 was used to determine strain change in the concrete prisms while the shear wave velocity and Young's modulus were calculated using the fundamental resonant frequencies methods in accordance with ASTM C215 Figure 2.2. In order to perform this test, an accelerometer with a 60 kHz resonant frequency was used in addition with a Data Physics

Quattro to record the data.

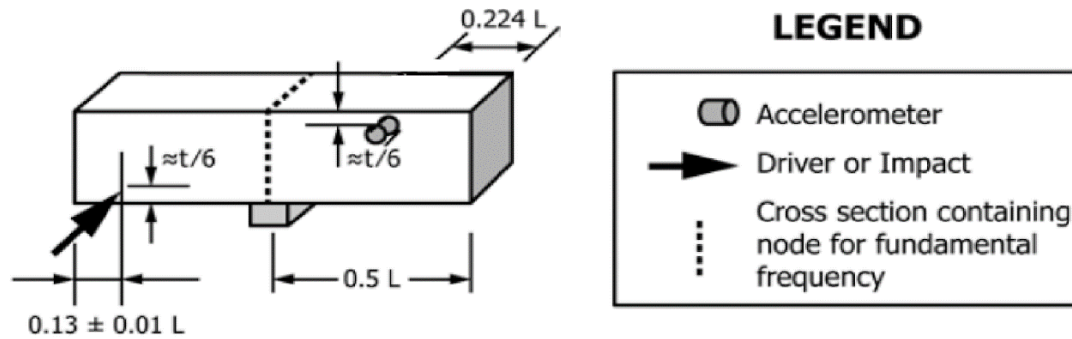


Figure 2.2 Schematic of fundamental resonant frequencies test (ASTM C215)

The Young's Modulus was calculated using the following formula according to ASTM C215-14

$$E = CMn^2 \quad (\text{Equation 1})$$

Where, M is the mass of the specimen, n is the fundamental transverse frequency obtained using Data Physics Quattro, C was calculated using the following formula.

$$C = 0.9464 \times \frac{l^3 T}{bt^3} \quad (\text{Equation 2})$$

Where l is the length of the prisms, t and b are dimensions of cross section of the prisms and T is a correction factor

Previous Results Summary

It was shown by Self (2017) that strain and shear wave velocity are inversely proportional as the strain increased the shear wave velocity decreased. In the early stages of concrete curing, the relationship between the shear wave velocity and strain is almost null due to the curing process. The deterioration in the concrete caused by alkali-silica reaction can be more accurately measured after a year. The addition of salts during the curing process decreased the shear wave velocity tremendously as a result of the acceleration of the alkali-silica reaction (Self 2017). This information is very useful because it can replicate what happens to roads during the winter season since salts are sometimes used as deicers. Thus, the environment is a very important factor in determining whether or not the alkali-silica reaction will have a great impact on a certain structure. For instance, buildings will not be exposed to these salts and therefore the alkali-silica reaction will have a lower rate of activation in comparison to the roads expose to

these salts. Balachandra (2011) explains that deicers can interact with the aggregates used to make concrete and therefore accelerate ASR.

3.1 Results and Discussion

In Figure 3.1, the Young's modulus of the concrete prisms is shown as a function of specimen age before the addition of the salts. The Young's modulus of each of the concrete prisms increases at a steady rate for each prism, until the prisms reach an age of approximately 28 days. At 28 days, the 40R prisms Young's modulus rate of increase slows and the modulus of the remaining prisms continues to increase over time. After 28 days, the Young's Modulus of the 20C and 0C prisms keep increasing very slowly, showing very small incremental changes. Additionally, 20R is the first concrete prism to show a significant drop in Young's modulus of 7% between 28 and 140 days, while the 40R prisms had a 11% drop between 140 and 168 days. Moreover, 40C prism was the second prism to show a drop of 3% between days 112 and 196. Thus, the speed and extent of the loss are based on the reactivity of the specimen (Swamy 1988). The 40R and 20R prisms start increasing at 168 and 140 days respectively. This could be due to the self-healing properties obtained from the hydration products that ASR generates (Sargolzaei 2011). In a separate study Rivard (2009) indicated that the Young's modulus of the non-reactive specimens increased by 4% between 21 and 322 days, while in this study the 0C and 20C prisms increased by 5% and 4% respectively when they reached 280 days. Therefore, the least reactive specimens 0C and 20C are showing the same trends as a non-reactive specimen in Rivard's study. Rivard also noticed that the reactive specimens were reduced by 12% between 21 and 322 days, while 40R, which is the most reactive specimen in this study, decreased by 11% between 140 and 168 days. Self (2017) explains that the shear wave velocity for 0C and 20C prisms increased during the entire recording period before the addition of the salts while the shear wave velocity for the most reactive specimens (20R, 40C, 40R) decrease for short periods of times which Self (2017) described as less than 100 days. Figure 3.2 shows the shear modulus from this experiment as a function of age before the salts were added. This graph shows the same trend as Figure 3.1. The decrease in shear modulus is similar to the decrease in Young's modulus, and they both start to decrease at the same age for the 40R and 20R prisms. The decrease in shear modulus for 40C, 20R, and 40R prisms are 3.5%, 10% and 9%, respectively. Thus, both measurements can be used as good estimates to assess ASR damage.

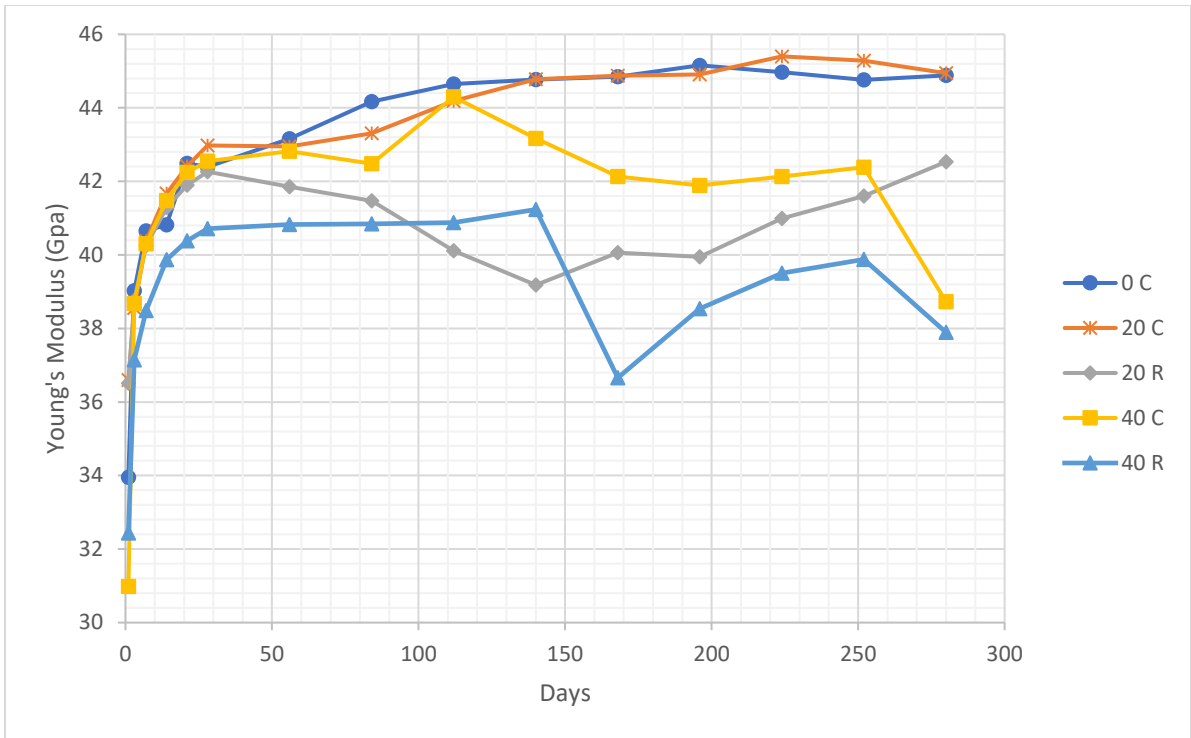


Figure 3.1 Concrete prisms age versus Young's modulus before the addition of the salts.

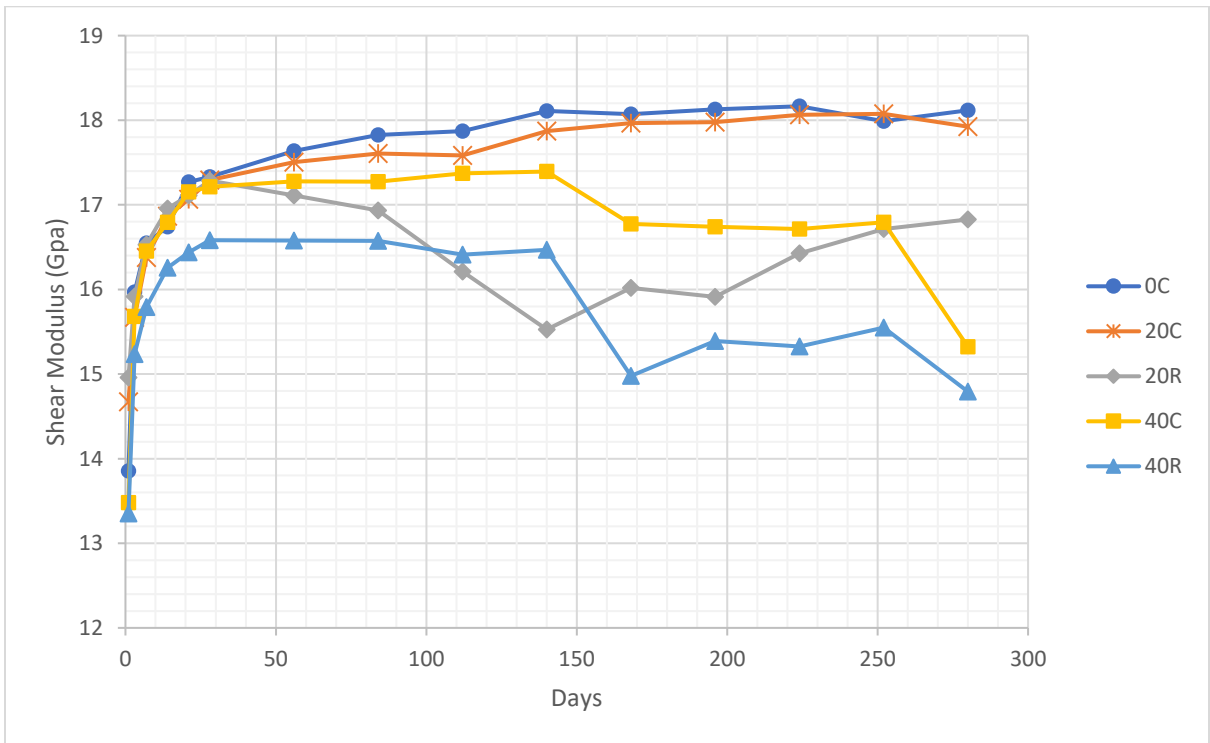


Figure 3.2 Concrete prisms age versus shear modulus before the addition of the salts.

In Figure 3.3, the strain percent of the concrete prisms is shown as a function of prism age before the addition of the salts. This information correlates with the information found in Figure 3.1 because the strain percent increases as the Young's modulus decreases following opposite trends. In fact, Young's modulus can be defined as axial stress divided by axial strain, so that the strain increases as the Young's modulus decreases. Additionally, the strain percent starts increasing at the same age the Young's modulus start decreasing for the most reactive specimens 20R and 40R which start increasing at 28 and 140 respectively. Moreover, the two least reactive concrete prisms show almost no change before the addition of salts because the highest strain value the 20C and 0C prisms reached is in between 0.038 and 0.02. The 40C prisms percent strain starts increasing after 140 days while the Young's modulus starts decreasing after 112 days. Therefore, this prism's internal damage is detected 29 days before any external physical change occurred by using the Young's modulus of the prism. Thus, as Swamy (1988) describes in his article, Young's modulus shows changes occurring inside the structure before any expansion could be measured. On the other hand, Self (2017) found a strong correlation between shear wave velocity decrease and strain percent increase. He explains that when the prisms reach 200 days, 20R and 40C prisms overlap in the shear wave velocity graph and also overlap in the strain percent graph at the same age. This corroborates Self (2017) point that shear wave velocity and strain have the same behavior which are indicators that shear wave velocity and strain are well correlated. The highest strain percent values for the most reactive specimens 20R, 40C, and 40R are between 0.1 and 0.09 at 280 days and based on ASTM C1293 if the concrete specimen reaches a strain percent greater than 0.04% before a year it is considered "potentially detrimentally reactive." Self (2017) explains that if shear wave velocity starts decreasing before the 0.04% strain is reached, can be another indicator that those concrete prisms are "potentially detrimentally reactive." The Young's modulus can function as a similar indicator as shear wave velocity in this instance. Therefore, shear wave velocity and Young's modulus can provide an earlier assessment of the general structure before the strain percent can increase. However, the Young's modulus seems to decrease earlier than the shear wave velocity based on results obtained from 40C prism.

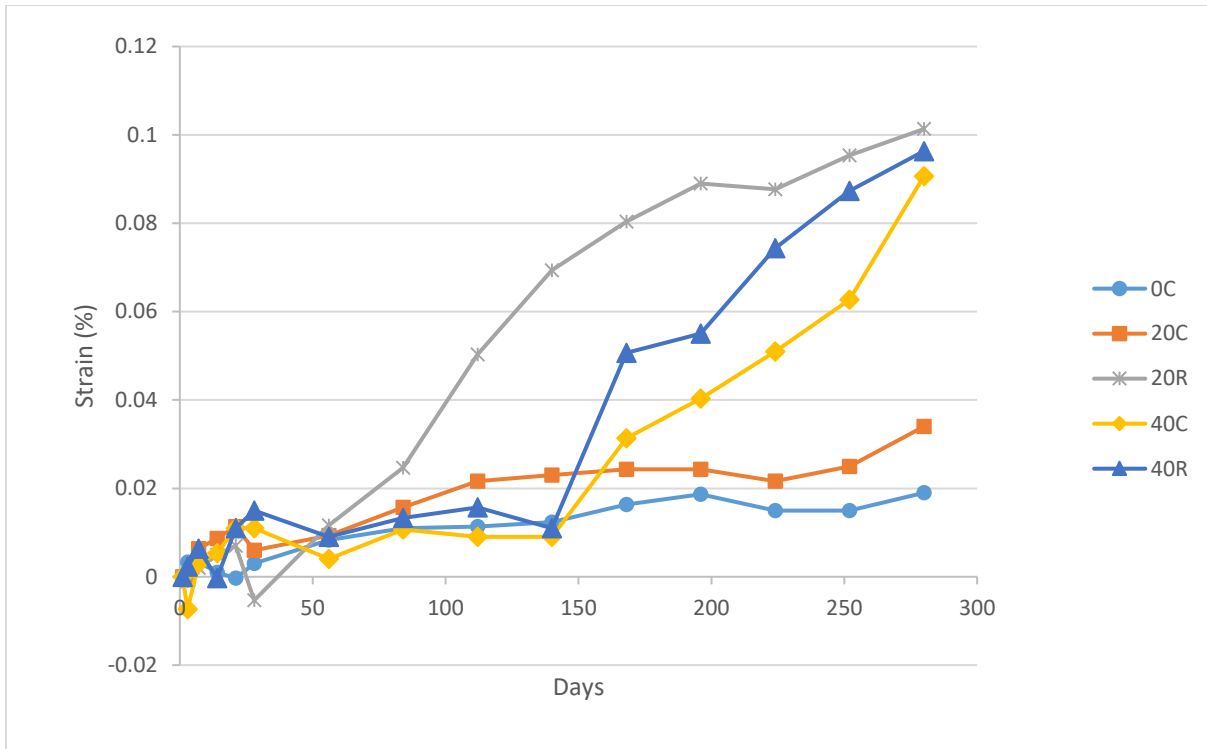


Figure 3.3 Strain percent change before the addition of salts.

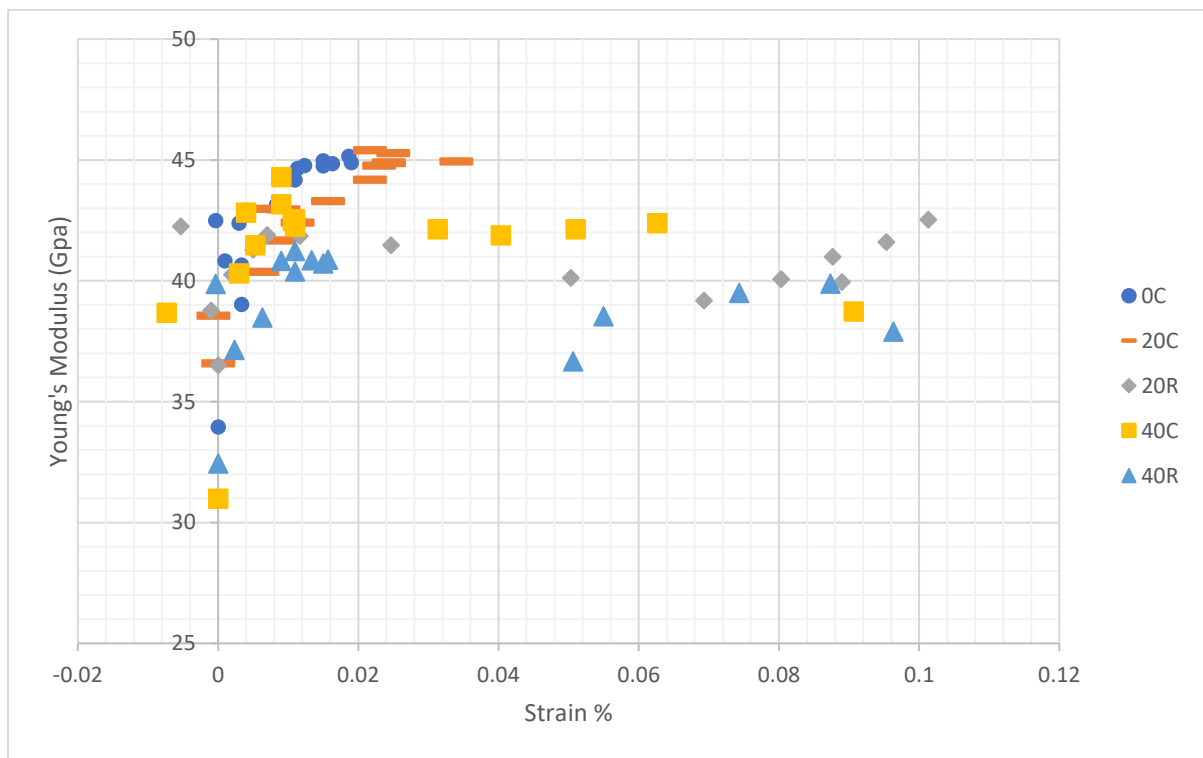


Figure 3.4 Young's Modulus versus strain before the addition of the salts.

In Figure 3.5, Young's modulus and strain values are shown before and after the addition of salts, which were added between 300 and 330 days. These graphs show a very strong relationship between Young's modulus and strain since the specimen with the highest strain values have the lowest Young's modulus and vice versa. The shear wave velocity and strain graphs in Self (2017) experiments follow the same trend as the Young's modulus and strain graphs. After 300 days, significant changes are observed in both graphs in that the Young's modulus decreased, and strain increased greatly. This increase in ASR rate, is a result of the salts acting as a catalyst in the reaction. In Self (2017), the most reactive specimens, 40R, 20R, and 40C, had a higher rate of reaction and strain percent change than the least reactive specimen 0C and 20C. For instance, even with the support of the salts, the change in strain for the 0C prisms took more than 400 days to reach 0.1% strain compared to the 0.7% of the 40R specimens. The shear wave velocity vs strain graph follows the same pattern as the Young's modulus vs strain graph. The least reactive specimens, 0C and 20C took the longest to show any significant change in Young's modulus and strain after the salts were added. Thus, it can be inferred that the least reactive specimens took longer to deteriorate than 40R, 20R specimen.

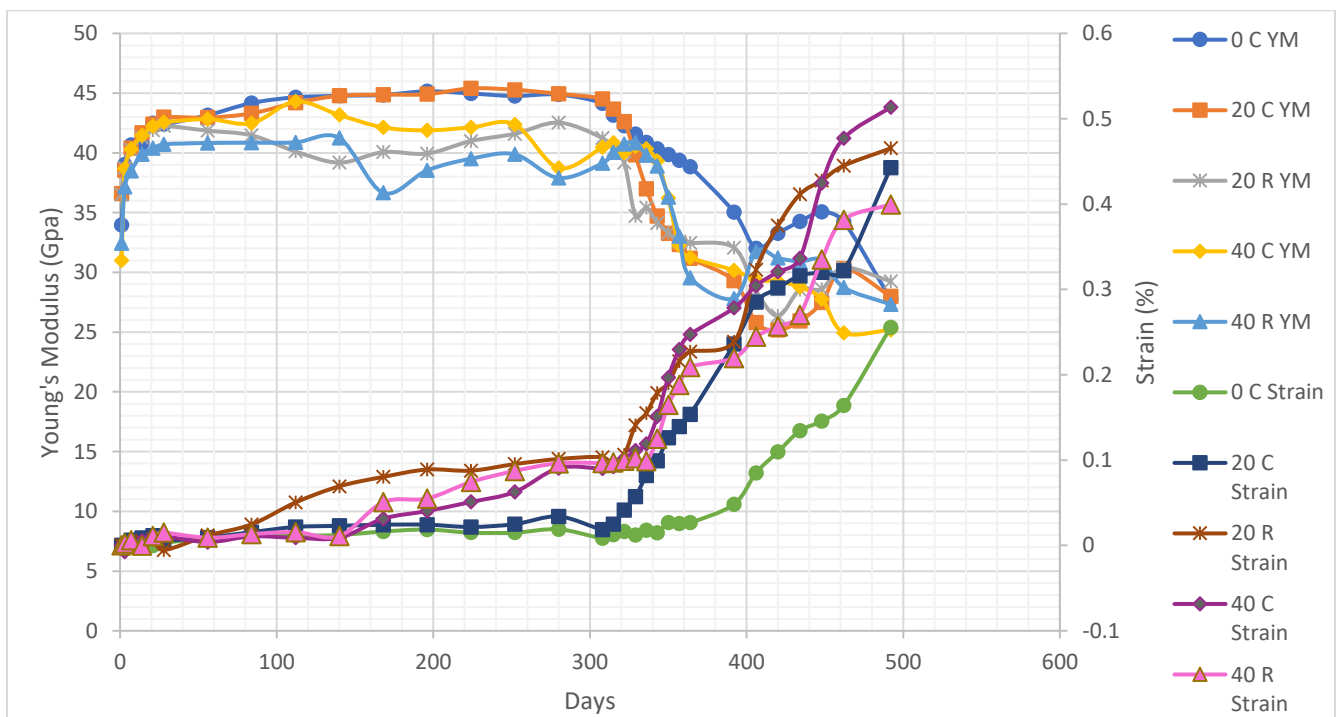


Figure 3.5 Young's modulus and strain before and after the addition of the salts.

Table 3.1 shows the maximum Young's modulus and the days it took the specimens to reach these values. All maximum Young's modulus values occur between 112-280 days which occurs before the addition of the salts at 300 days. These values coincided with what was expected from the experiment because as the salts were added to the reaction the strain rate increases which causes the Young's modulus to decrease. The concrete prisms with the higher Young's modulus measurement are the two least reactive specimens, 0C and 20C. And the most reactive specimens 40R, 20R and 40C have the lowest Young's modulus values of 41.237 Gpa, 42.533 Gpa and 44.29 Gpa, respectively base on the reactivity level. Comparing Self (2017) and this study, the Young's modulus and shear wave velocity values follow the same trend, but the times until the maximum values are reached, are different. The least reactive specimens 0C and 20C achieved their maximum Young's modulus before they reached their maximum shear wave velocity. In the contrary, the most reactive specimens 40R, 20R and 40C attained their maximum shear wave velocity before they reached their maximum Young's modulus. Shear wave velocity increases during the curing process, which consist in maintaining the specimen moist at the right temperature (Boyd 2005). The rate of the curing process can be affected by ASR in the later phases of the curing process. Thus, "the shear wave velocity drops more due to ASR than it increases due to curing." (Self 2017). On both experiments right after the values of shear wave velocity and Young's modulus peak, a drop is observed. However, the shear wave velocity reaches the peak before the Young's modulus does, and hence leading to an earlier decrease in shear wave velocity than Young's modulus. Thus, shear wave velocity can be more sensitive than Young's modulus to determine ASR damage because it is an earlier indicator of internal concrete deterioration.

Table 3.1 Maximum average Young's modulus from each set of prisms.

	Maximum Young's Modulus (Gpa)	Strain at Maximum Young's Modulus (%)	Days when Maximum Young's Modulus was reached
0C	45.156	0.0187	196
20C	45.400	0.0217	224
20R	42.533	0.1013	280
40C	44.299	0.009	112
40R	41.237	0.011	140

A linear trend in Figure 3.6 shows the relationship between the normalized Young's modulus and strain percent. The Young's modulus values used in this graph are obtained from the data before the salts were added, around 280 days and after 56 days when Young's modulus start decreasing. The addition of the salt accelerates the rate of the ASR and therefore major damage take place inside the concrete specimen. This internal damage is represented by the drastic decrease in Young's modulus after 300 days. These Young's modulus measurements were eliminated from the graphs because they represent an abnormal behavior of Young's modulus (Self 2017). The values of the Young's modulus were normalized by using Equation 2.

$$z = \frac{x_i - \mu}{\sigma} \quad (\text{Equation 2})$$

Where x_i is the Young's modulus value, μ is the average value of all specimen between 56 and 280 days and σ is the standard deviation of the specimen at the same age and z is the normalized Young's modulus.

The Young's modulus was normalized to reduce data redundancy and to develop an overall relationship of all concrete prisms set. This normalized relationship is show in Equation 3.

$$G = -6.394\varepsilon + 1.0772 \quad (\text{Equation 3})$$

Where G is Young's modulus and ε is the strain value. The R^2 value of the relationship is 0.6842, which indicates a reasonable relationship between Young's modulus and strain in the concrete prisms.

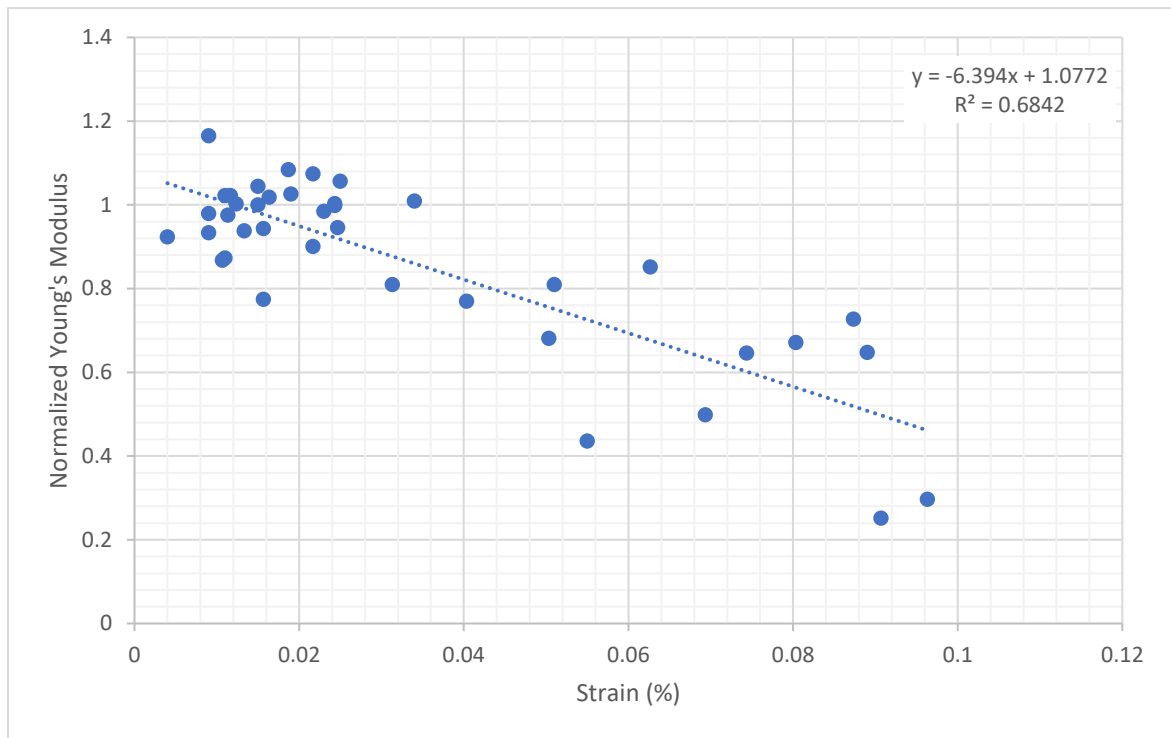


Figure 3.6 Normalized linear relationship between Young's modulus and strain

4. Conclusion

The results of the study indicate that Young's modulus follows the same trend as shear wave velocity for concrete prisms affected by ASR. Young's modulus also has an inversely proportional relationship with the strain percent as the strain percent increases the Young's modulus decreases. Before the addition of the salts, the Young's modulus percent decrease is very similar to the percent decrease in shear modulus, which proves the relationship between Young's modulus and shear modulus. The maximum Young's modulus were higher for the least reactive specimen than the most reactive and this is also true for the maximum shear wave velocity values. Additionally, the maximum shear wave velocity values occurred before the maximum Young's modulus values occurred. Young's modulus and strain change drastically after the salts were added because they accelerate the reaction rate. The decrease in Young's modulus occurred before the strain percent is considered potentially detrimental at 0.04%. Therefore, Young's modulus and shear wave velocity can be used as an earlier indicator to assess

ASR damage in concrete. Young's modulus and shear wave velocity lead to the same results, so they are both good measures to assess ASR damage in concrete. They could be used interchangeably or as a check point to corroborate the information obtained from the other method.

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