TECHBRIEF

Accelerated Determination of ASR Susceptibility During Concrete Prism Testing Through Nonlinear Resonance Ultrasonic Spectroscopy

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Introduction

The alkali-silica reaction (ASR) is one form of deterioration that may significantly reduce the service life of concrete structures. Currently, ASR susceptibility of aggregate sources is most commonly assessed through length change in the concrete or mortar specimens over time while subjected to standardized acceleratory conditions. The standard concrete prism test (i.e., ASTM International (formerly American Society for Testing and Materials (ASTM) C1293) is considered the most representative of field performance.[1] However, one significant practical drawback of that test is its long duration, which is 1 year to assess aggregate reactivity and 2 years to assess mitigation measures. The standard accelerated mortar bar tests (AMBT) are considerably quicker to perform but have not proven reliable in all cases, leading some agencies and owners to implement alternate test durations and/or expansion limits.

For both the standard mortar and the concrete tests, another issue is the use of a final expansion measurement as the sole measure of aggregate reactivity, leading to difficulties in predicting field performance when final expansion results are ambiguous (e.g., very close to the limits, or on an upward trajectory). The objective of this research is to develop a reliable measurement technique that can more quickly quantify damage associated with ASR in concrete specimens while also providing an assessment of the accumulated damage. The developed technique, nonlinear impact resonance acoustic spectroscopy (NIRAS), is based on measurements of the nonlinear acoustic or vibration responses of concrete specimens.

The research has been coducted on laboratory-cast concrete prism specimens containing both fine and coarse aggregates obtained from different sources to provide a spectrum of reactivity for assessment through the developed NIRAS technique. The NIRAS measurements were performed while the specimens were undergoing the ASTM C1293 concrete prism test (CPT), and the results from NIRAS measurements are compared with those expansion results.

Approach

Sample Preparation: Mix Design and Concrete Prism Specimens

All specimens were cast according to the ASTM C1293 standard. The mix design matrix, shown in table 1, was developed to examine a range of ASR behavior, including

Table 1. Mix design matrix for NIRAS and ASTM C1293 concrete prisms

Mix ID.	Coarse Aggregate	Fine Aggregate	Supplementary Cementing Materials
Mix 1 NR/NR	Limestone, GA	Limestone, GA	—
Mix 2 HR/NR	Las Placitas, NM gravel	Limestone, GA	—
Mix 3 NR/HR	Limestone, GA	Las Placitas, NM gravel (crushed)	—
Mix 4 HR/NR	Spratt limestone, Canada	Limestone, GA	—
Mix 5 NR/HR	Limestone, GA	Spratt limestone, Canada (crushed)	—
Mix 6 NR/MR	Limestone, GA	Alabama sand, AL	—
Mix 7 NR/MR	Limestone, GA	Central Illinois Sand, IL	—
Mix 8 HR/NR—25% FA	Spratt limestone, Canada	Limestone, GA	25% Class FA
Mix 9 NR/HR—25% FA	Limestone, GA	Spratt limestone, Canada (crushed)	25% Class FA
Mix 10 NR/HR—25% FA	Las Placitas, NM gravel	Limestone, GA	25% Class FA

NR = nonreactive
MR = potentially or "may be" reactive
HR = moderately to highly reactive
FA = fly ash

Table 2. ASTM C1260 results for the aggregates examined		
Aggregate Source	**14-day AMBT Expansion (%)**	**AMBT Classification**
Limestone, GA	0.0787	Innocuous
Las Placitas, NM gravel	0.8533	Potentially deleterious
Spratt limestone, Canada (crushed)	0.2661	Potentially deleterious
Alabama sand, AL	0.1555	Innocuous or potentially deleterious
Central Illinois sand, IL	0.2088	Potentially deleterious

the combination of two non-reactive aggregates (Mix 1) and the use of aggregates termed "moderately to highly reative" (HR) and "potentially (or may be) reactive" (MR) aggregates in combination with non-reactive aggregate (NR). Expansion at 14 days was measured during ASTM C1260 testing (see table 2).[2] According to ASTM C1260, expansion at the end of the test that is less than 0.10 percent indicates innocuous behavior, expansion greater than 0.20 percent indicates potentially deleterious expansion, and expansion between 0.10 and 0.20 percent may be innocuous or deleterious in field behavior. Considering the ASTM C1260 results, along with historical aggregate standard test results and field performance history of these aggregates, the aggregates were classified preliminarily as NR, MR, or HR. Table 2 presents these classifications, along with other details on the concrete prism mixtures, including the sample naming scheme. The nonreactive aggregate used in all the mix designs is a limestone from Adairsville, GA. In addition, an ASTM C 150 Type I cement with alkali equivalent of 0.88 percent, meeting the ASTM C1293 requirements, was used in casting CPT samples; the alkali content of the concrete was "boosted" to 1.25 percent by mass cementitious materials, in accordance with the standard.

As specified in ASTM C1293, concrete prisms (3 by 3 by 11.25 inches (76 by 76 by 285 mm)) were cast with a water-to-cement ratio of 0.45. The gradation for coarse aggregate was as specified in ASTM C1293. For as-received fine aggregates and crushed coarse aggregates used as fines, the gradation is adjusted to obtain a fineness modulus of 2.71 for consistency among the concretes. The samples were initially cured for 24 hours in a moist environment and subsequently stored over water in a sealed container, at 100.4° F (38° C), to accelerate ASR.

NIRAS Measurement: Theoretical Background and Damage Parameter

Microcracks distributed in concrete can be envisioned as forming a network of soft bonding elements that are the source of the strong nonlinear acoustic behavior of concrete. Using the phenomenological model for hysteresis and classical nonlinear constitutive relations, the general nonlinear stress–strain relationship can be shown as the equation in figure 1:[3,4]

Figure 1. Equation. Nonlinear stress–strain relationship

$$\sigma = \varepsilon \cdot E_0 \left[1 + \beta\varepsilon + \delta\varepsilon^2 + \alpha\left(\Delta\varepsilon + \varepsilon \cdot \operatorname{sgn}(\dot{\varepsilon})\right) \right]$$

where σ is stress, ε is strain; E_0 is the linear elastic modulus; β and δ are the coefficients of quadratic and cubic nonlinearity; α is the measure of the material hysteresis; $\Delta\varepsilon$ is the strain amplitude (during a dynamic excursion); $\dot{\varepsilon}$ is the strain rate; and $\operatorname{sgn}(\dot{\varepsilon}) = 1$ if $\dot{\varepsilon} > 0$, -1 if $\dot{\varepsilon} < 0$, and 0 if $\dot{\varepsilon} = 0$. One of the consequences of this nonlinear stress–strain relationship is the excitation amplitude dependent resonance frequency of a concrete specimen.

Figure 2 shows resonance spectra obtained for different levels of excitation of a CPT specimen. The resonance frequency of the specimen (represented as a peak in each spectrum) shows a downward shift with the increase of impact strengths. It has been shown that the amount of the downward shift is proportional to the amount of damage occurring in the specimen in terms of the density of microcracks.

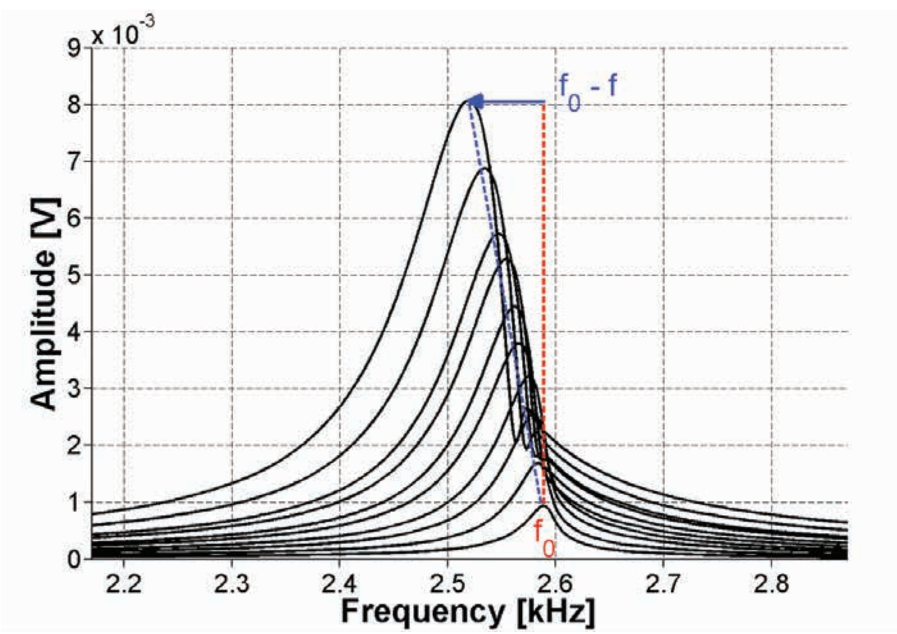
Therefore, a nonlinearity parameter that characterizes the amount of damage at a certain instant is defined as shown in equation in figure 3:[4]

Figure 3. Equation. Nonlinearity parameter characterizing amount of damage

$$\eta = \left(\frac{f_0 - f}{f_0} \right) / A$$

where f_0 is the linear resonance frequency, f is the resonance frequency at an increased excitation amplitude, and A is the amplitude

Figure 2. Graph. Shift of resonance frequency for increasing excitation strength (measurements performed on a typical CPT specimen).



of excitation. Note that η is the negative of the slope of $(f_0 - f)$ versus the amplitude (the y-axis) in figure 2.

Because the nonlinearity is attributed to nonlinear interactions (clapping and Hertzian contact) of crack surfaces, relatively large and open cracks will not contribute to nonlinearity. Under this assumption, the above nonlinearity parameter can be thought of as an "instantaneous" measure of nonlinearity. A "cumulative" nonlinearity (η_c) or damage parameter can then be measured by integration, using the equation shown in figure 4.

Figure 4. Equation. Integral to calculate "cumulative" nonlinearity

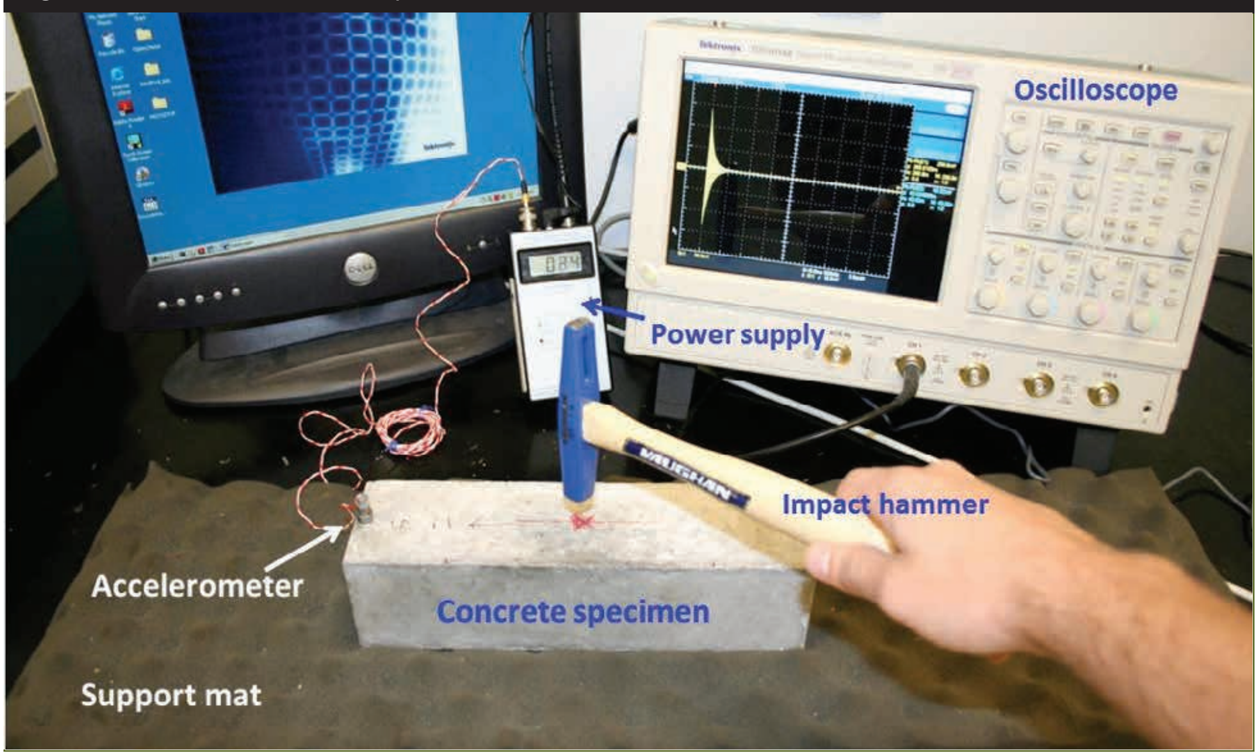
$$\eta_c = \int_0^t \eta(\tau)d\tau$$

These two parameters are used in this research as indicators of the amount of damage due to ASR that has accumulated in the specimens.

NIRAS Measurement: Experimental Method and Procedure

The experimental setup is similar to the ASTM C215 procedure for the measurement of the transverse resonance frequency.[5] The specimen is placed on a 1.5-inch (38 mm) thick support mat to allow the specimen's free vibrations. A 5-oz. (140-g) hammer is used to strike the sample in its center, as shown in figure 5. A miniature accelerometer (PCB 353B13) is attached using super glue to one end of the specimen, at the midline, where the response is at a maximum for the transverse mode. The NIRAS measurements begin 1 minute after the attachment of

Figure 5. Photo. NIRAS test setup



the accelerometer, and the signals are then captured using an oscilloscope (Tektronix TDS5034B) and analyzed using Matlab®. The signal duration captured by the oscilloscope is 0.4 s, which allows a complete decay of the response signal (see the signal shown on the oscilloscope screen in figure 5), with a sampling rate of 500 kilo Samples/second (kSa/s). The signal is then "zero-padded" and analyzed using the fast Fourier transform. Figure 2 shows a set of typical resonance spectra measured from a CPT specimen. The downward shift of resonance frequency is obvious in the figure. The quantities f_0 and $(f_0 - f)$ can be easily extracted from this figure, and then the nonlinearity parameter η can be calculated using the equation in figure 3. The repeatability and robustness of the NIRAS measurement setup were validated using an aluminum specimen with similar dimensions.

Results

Expansion Results

This section briefly presents the expansion measurement results for the concrete mixtures described in table 2. Results of all the expansion measurements are shown in figure 6, with figure 7 showing more detail for the lower-expanding mixes. (Note that the legend for the two figures is the same. Also, the difference in y-axis scaling between the two figures should be noted.) When expansion during CPT exceeds 0.04 percent by 1 year, aggregates are classified as reactive. For assessments of mitigation measures, such as the use of fly ash (FA), the limit is 0.04 percent at 2 years.

The preliminary AMBT results and the CPT results for the HR mixtures, as well as the NR Mix 1, generally show good agreement. That is, the aggregates identified as

Figure 6. Graph. All ASTM C1293 expansion results

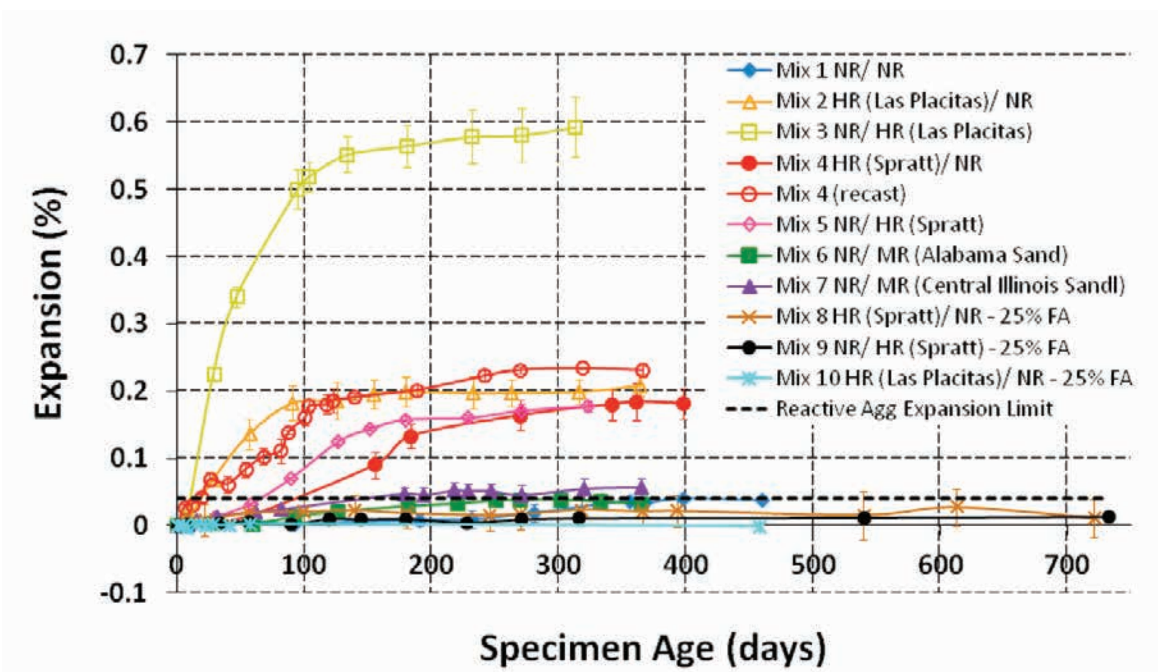
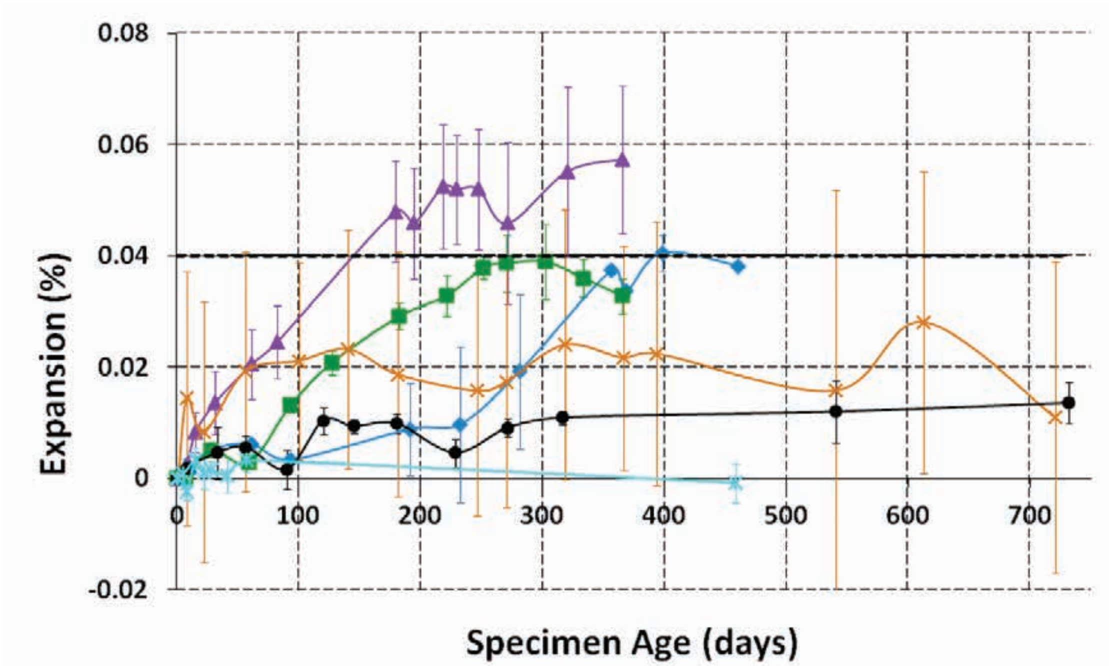


Figure 7. Graph. Greater detail in ASTM C1293 expansion results for the less expansive mixes



"potentially deleterious" in AMBT—those used in mixes 2, 3, 4, and 5—are identified through CPT as "reactive." Through comparison, Mix 7 was also identified as "reactive" by CPT. The expansion in Mix 7 exceeded the CPT limit at about 150 days, but its potential for reaction is less clear in the ABMT, with a 14-day expansion at just about 0.2 percent, putting it in the "innocuous to or potentially deleterious" category. This discrepancy demonstrates some of the challenges associated with characterizing aggregates from their expansion.

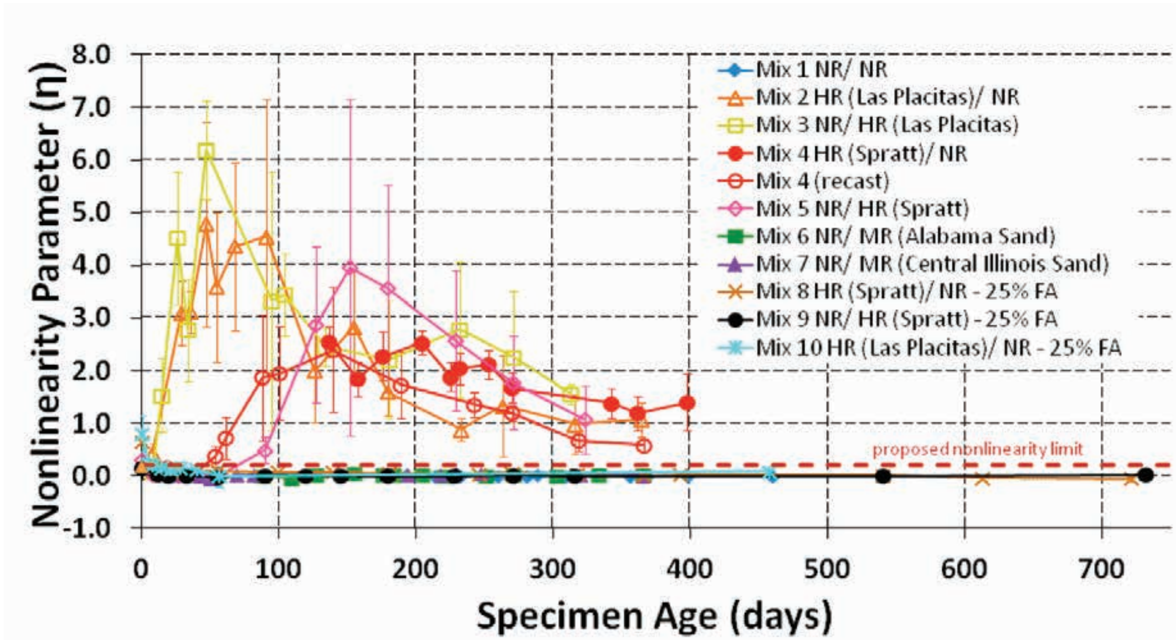
The average expansion of mixes 1 and 6 has not crossed the expansion limit at 1 year; therefore, these are classified as non-reactive by the CPT. Mix 6 was expected to experience more expansion than Mix 1 because, according to ASTM C1260, the aggregate in Mix 6 was classified as innocuous or potentially deleterious. According to these concrete prism results, the aggregate is nonreactive but it does come very close to the expansion limit, again perhaps demonstrating some of the challenges associated with determining reactivity through expansion measurements alone.

The 25-percent replacement of cement with FA in mixes 8 and 9 appears to be effective in mitigating expansion with the Spratt aggregate because the expansion limit has not been crossed. In comparison, mixes 4 and 5, which use the same aggregate, crossed the limit before 100 days.

NIRAS Results

Figure 8 presents the NIRAS results. The measured nonlinearity parameter, for the same three specimens as were used for the CPT expansion measurements, is

Figure 8. Graph. NIRAS results for all mixtures



averaged and plotted at each test date. For this representation, the nonlinearity parameter is shown as a function of the time that samples were exposed to ASTM C1293 testing conditions.

Based on these results, derived from a limited range of aggregates and with a limited range of binder compositions, a preliminary limit of 0.2 during the standard test duration has been proposed to distinguish between alkali reactive and non-reactive aggregates, cast and tested according to ASTM C1293. However, significant further investigation—including ruggedness testing, round-robin testing of precision and bias, and a comprehensive assessment of more aggregate types—is clearly needed to determine the microstructural changes that contribute nonlinearity as well as to better assess what level of nonlinearity can be considered to distinguish between innocuous aggregates and those detrimental to long-term performance.

The results show that the NIRAS technique confirms the ASTM C1293 reactivity classification based on expansion results for the nonreactive and reactive mixtures. For aggregates initially classified as HR, once again measures of expansion and nonlinearity are in agreement. For both Mix 1 and Mix 6, the average expansion of the specimens at 1 year is very close to the 0.04 percent expansion limit in ASTM C1293, indicating a nonreactive aggregate by that measure. The classification of aggregate in Mix 6 is more ambiguous because it exceeded the lower 0.1-percent expansion limit in AMBT. NIRAS shows the non-linearity of both Mix 1 and Mix 6 specimens has remained very close to zero throughout the year of testing, indicating these are nonreactive aggregates. Although the expansion for any concrete sample, including the nonreactive mixes, increases as the duration of the test increases, the nonlinearity does not change for a nonreactive aggregate, providing a more definitive and accurate result.

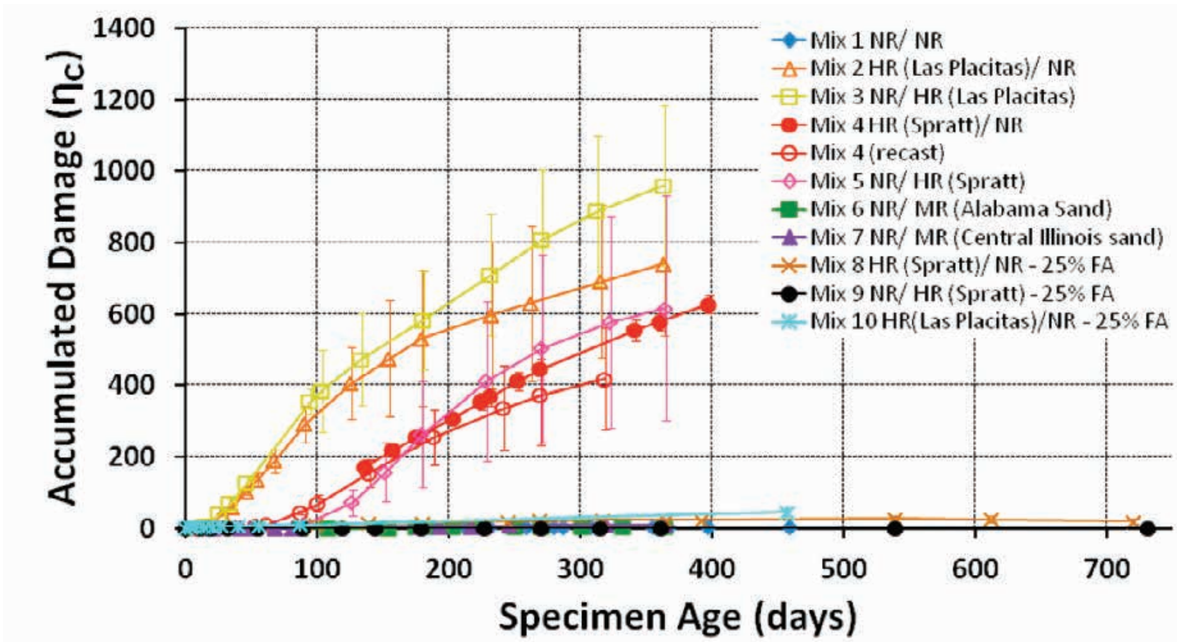
In some cases, there is an indication of earlier detection of reactivity using nonlinearity measured through NIRAS. Comparing data for Mix 2 in figure 6 and figure 8, it can be seen that the NIRAS technique is capable of identifying ASR sooner than the expansion measurements; nonlinearity is detected at 8 days while the expansion limit is crossed at about 25 days. Mix 7 is the only mix for which the nonlinearity measurements contradict expansion measurements. The expansion limit has been crossed for that mix but nonlinearity remains negligible throughout the 1-year test. Independent petrographic study on this mix validates the nonlinear measurements (see full report for details). Table 3 summarizes the AMBT, CPT, and NIRAS results for the aggregates examined.

For reactive mixes, in addition to the early increase in nonlinearity, a decrease in the nonlinearity parameter has been observed at later ages. This decrease is not yet fully understood, but it is postulated that a decrease in nonlinearity could be accompanied by increasing size (e.g., width) of cracks. The measured nonlinearity comes from the nonlinear behavior of cracks through the interaction of crack surfaces. As a result, when a crack widens, the crack faces may no longer interact and will contribute less to measured nonlinearity.

Table 3. Summary of reactivity classifications based on AMBT, CPT, and NIRAS

Sample	Aggregate reactivity based on ASTM C1260	Aggregate reactivity based on ASTM C1293	Aggregate reactivity based on NIRAS
Mix 1	Innocuous	Nonreactive	Nonreactive
Mix 2	Potentially Deleterious	Reactive	Reactive
Mix 3	Potentially Deleterious	Reactive	Reactive
Mix 4	Potentially Deleterious	Reactive	Reactive
Mix 5	Potentially Deleterious	Reactive	Reactive
Mix 6	Innocuous or Potentially Deleterious	Nonreactive	Nonreactive
Mix 7	Potentially Deleterious	Reactive	Nonreactive

Figure 9. Graph. Cumulative nonlinearity for all mixes



It is also noteworthy that this decrease in nonlinearity appears to occur at about the same time the expansion rate starts to decrease and level off. Perhaps the same phenomenon is responsible for the eventual decrease in expansion rate and decrease in nonlinearity observed in the results.

Another way to represent the nonlinearity data—and one that shows even greater distinction between the reactive and non-reactive aggregates—is through a measure of accumulated damage, η_c. Taking the measured nonlinearity as an instantaneous measure, the data are integrated, as described above, to find the accumulated damage, as shown in figure 9. Using the accumulated damage for these mixtures, some distinctions can be seen between the mixtures that could not be seen from the instantaneous nonlinearity in figure 8. The expansion measurements, figure 6, show measurement variations for the recast Mix 4 and the original Mix 4. Although the cause of this discrepancy is unknown, it is evident that nonlinearity measurements remain relatively unaffected and may be more robust.

The expansion measurements seem to indicate a faster rate of reaction when the reactive aggregate is used as a fine aggregate compared with when used as received (a coarse aggregate). An exception is the recast Mix 4, which shows no observable effect of the size of the reactive aggregate on the NIRAS measurements. This can be beneficial in laboratory testing because these results suggest that there is no effect of aggregate size on the results of reactivity classifications. Further testing is needed to validate these observations, however.

The standard deviation, represented by error bars, shows the variability in the three samples tested for each mix. Both the expansion measurements and measurements of η show a general trend of increasing standard deviation with increased expansion or nonlinearity. Because of inherent heterogeneities, the cast prisms are not identical to each other, even within the same mix. As a result, each sample represents a different material system that can accumulate damage in different ways. Because of the higher sensitivity of NIRAS, the standard deviation is larger for reactive mixes.

Conclusions

- NIRAS measurements have shown a clear distinction between reactive and non-reactive aggregates and concrete mixtures. For more reactive cases, there is evidence of earlier detection of ASR-related damage with the NIRAS testing technique than with concrete prism expansion.
- NIRAS has also been proven to be a powerful non-destructive testing tool to rapidly detect microcrack-type damage (regardless of the cause) in concrete in an early stage of the material degradation. Based on the current body of research, this test should be used as a supplement to other standard testing. Additional research and testing can be used to assess whether NIRAS can be used as an alternative test.
- With some aggregate types, a higher rate of expansion is measured with aggregate that has been crushed than in the as-received condition, showing a potential effect of aggregate size. The NIRAS measurements, however, do not appear to be affected by the reactive aggregate size and show the potential to be used to evaluate job-specific aggregates, while also eliminating the need for the time-consuming crushing and grading processes.
- Two nonlinearity parameters are defined: one (η) that characterizes the rate of damage development at a certain instant and another (η_C) that characterizes the amount of damage accumulated up until that time. Based on the experimental results for a limited number of aggregates—albeit with various levels of reactivity—it is proposed that the aggregate under assessment can be considered alkali-reactive if the nonlinearity parameter of its concrete prism specimen measures 0.2 or more at any time during the 12-month test period. Nonlinearity parameters between 0.05 and 0.2 may suggest some potential for ASR, and the aggregate should be further evaluated. These proposed limits, however, must be verified through a more comprehensive evaluation of a broader range of aggregates and also through round-robin testing.

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