ULTRA-ACCELERATED ASSESSMENT OF ALKALI-AGGREGATE REACTIVITY BY NONLINEAR ULTRASONIC TECHNIQUES

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Abstract

The objective of this research is to develop an ultra-accelerated testing method for predicting the potential alkali-silica reactivity of aggregates using advanced ultrasonic techniques. Standard accelerated mortar bar testing (AMBT) is coupled with an ultrasonic nonlinear acoustical modulation method, with the aim of distinguishing between aggregate of varying alkali reactivity at earlier times. Due to its sensitivity to microcracking, the nonlinear acoustic method is able to distinguish damaged specimens (exposed to aggressive conditions) from undamaged specimens. The distinction between the reactive and non-reactive aggregate is apparent as early as 4 days when compared to the current 14-day test period of the AMBT. Further, the method is able to differentiate between three aggregates of varying reactivity, also at early ages. These results demonstrate the potential of nonlinear acoustic waves to provide a more rapid and quantitative evaluation of the potential for alkali-aggregate reactivity.

Keywords: damage, expansion, nonlinear ultrasound, non-destructive test

1 INTRODUCTION

With the gradual depletion of demonstrated non-reactive aggregate sources, the use of marginal aggregates is growing. As a result, testing to screen the alkali-reactivity of aggregates has become critically important. The most reliable test method – the concrete prism test – takes one year for normal concrete mixes and two years for mixes with supplementary cementing materials; the long test duration makes it impractical to be routinely used in the construction industry to screen aggregate. The more rapid accelerated mortar bar test (AMBT) takes only 16 days but is still not used with regularity by materials producers to assess variations in aggregate reactivity. For example, reassessment of an aggregate source by AMBT may be required only every three years, or perhaps even less frequently [1]. This suggests that an even more rapid (or "ultra-accelerated"), but still simple, reproducible, and relatively inexpensive, test method is needed for routine screening of aggregate reactivity.

The coupling of traditional ASR testing with nonlinear acoustic techniques could provide a more rapid assessment of an aggregate's potential reactivity [2]. Nonlinear acoustic techniques have been successfully employed for the non-destructive assessment of cracks and damages in metals and alloys [3-4]. These results have demonstrated that nonlinear acoustic techniques are more sensitive than linear ultrasonics to the development of damage due to various factors, including fatigue load, ambient temperature and debonding in composite structures. More recently, nonlinear acoustic techniques have been used to detect microstructural features and flaws in cement-based materials [2].

Here, a nonlinear acoustic technique - the nonlinear wave modulation spectroscopy (NWMS) method - is examined for the assessment of ASR-induced damage in mortar bars. Aggregates of varying alkali-reactivity were examined by this non-destructive method to assess if the method (1) can measure accumulated damage by progressive ASR and (2) can effectively distinguish mortars with aggregates of different reactivity.

2 NONLINEAR ACOUSTIC THEORY

Linear acoustic methods have been traditionally used to detect cracks or flaws in materials [5-9]. Popular techniques include measurement of wave velocity and attenuation. One fundamental concern with the use of linear methods is that they are not able to detect microcracks, especially

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damage developed at early ages (e.g., in response to low stresses or a small number of cycles, in the case of fatigue) [10]. Linear acoustic methods are only able to detect large cracks which often result in the detection of damage only at later stages of deterioration. Hence, the development of nonlinear acoustic methods, which are more sensitive to microcracks than linear methods, is of great significance for damage investigation in various materials, including cement-based materials [11-12].

The primary assumption of the nonlinear technique is that a nonlinear stress-strain relation exists for the material examined [13-14]. Unlike the constant elastic modulus commonly used in a linear elastic constitutive equation, the elastic modulus (K) in the nonlinear method is expressed as a power series of strain (ε):

$$K(\varepsilon) = K_0(1+ \beta\varepsilon+ \delta\varepsilon^2+\ldots) \quad (1)$$

where the first term on the right side is the generally used linear stress-strain relation, and the second and third terms represent the nonlinear quadratic and cubic relation of stress and strain.

When nonlinear acoustic methods are applied to undamaged specimens, the nonlinear response to the incident wave is insignificant. Hence, the frequency of the resultant wave is the same as the frequency of the incident wave, and no other frequency components are generated. However, with the development of cracks and flaws, the nonlinear effect becomes more prominent, and the incident wave is distorted, producing accompanying harmonics in the resultant signal. Hence, when a signal with frequency f is transmitted through a damaged material, wave components with frequency $2f$, $3f$ etc. appear in the resultant signal. Furthermore, a relationship between the amplitude of the harmonics and fundamental wave can be obtained using the nonlinear acoustic theory. For instance, it can be proven that the amplitude of the second harmonic is linearly proportional to the material damage parameter and also to the square of amplitude of the fundamental wave:

$$U_2 \propto D\,(U_1)^2 \quad (2)$$

where U_2 and U_1 are the amplitudes of the second harmonic and fundamental waves respectively, and D is the nonlinearity (or damage) parameter of the material.

In the previous case, the second harmonic can be considered to be an interaction of the fundamental signal with itself. Similarly, the case of modulation between two waves with different frequencies (f_1 and f_2) can be solved in an analogous manner. Considering only the first order of nonlinearity in the resultant wave, the frequency components are generated at the summation and subtraction of two incident wave signals ($f_1 \pm f_2$). These new frequency components are called "sidebands", and their amplitude is linearly proportional to the amplitudes of incident waves and the material damage parameter:

$$U_3 \propto D\,U_1\,U_2 \quad (3)$$

where U_3 is the amplitude of the sideband.

Here, this nonlinear technique featuring modulation between two waves with different frequencies is used. This technique is known as the NWMS method. The ability of this method to measure increasing ASR damage, such as micro-cracking and aggregate/paste debonding, is the focus of this research.

3 SPECIMEN PREPARATION

The accelerated mortar bar test method was used for testing the potential reactivity of aggregates due to ASR and for testing the proposed ultrasonic test method. Specimens for expansion tests as well as ultrasonic measurements were cast according to the specifications of the AASHTO T 303 test for the detection of alkali silica reactivity of aggregates. The AASHTO T 303 method is commonly specified by U.S. state departments of transportation and varies marginally from the ASTM C 1260 method more commonly used by researchers, only in the water-to-cement ratio used to produce the mortars. Standard mortar bars of dimensions 25 mm by 25 mm by 285 mm were cast at water-to-cement ratio of 0.50 at a sand:cement ratio of 2.25. Type I portland cement was used for the tests and separate mortar bars sets were cast for the ultrasonic tests and for expansion measurements. Fine aggregates from different sources with varying alkali reactivity were used for preparation of the samples. The highly reactive, moderately reactive and low reactive aggregates were obtained from Texas, Alabama and Georgia in USA. The alkali-reactive component in the highly reactive and the moderately reactive aggregate was chert.

According to the standard, the mortar bars were cured at ~100% relative humidity for 24 hours, de-molded and then cured in water at 80°C for 24 hours. The expansion measurements were carried out according to the specifications in the AASHTO T 303. The mortar bars for the ultrasonic tests were taken out of the water bath and was cut to a length of 240 mm. The ends of the mortar bars for ultrasonic measurements were polished to ensure proper contact of the bar with the transducers while taking the ultrasonic measurements. After the first set of ultrasonic measurements, all the mortar bars including the bars for expansion measurements were immersed in 1 N sodium hydroxide solution at 80°C. Subsequent expansion and ultrasonic measurements were carried out at 24 hours intervals, until 14 days of exposure. Prior to taking ultrasonic measurements, the mortar bars were placed for 1/2 hour in an environmental chamber at a temperature of 23°C and 50% relative humidity. Though a deviation from the standard AASHTO T 303 procedure, it was necessary to condition the ultrasonic specimens to ensure consistency in the moisture content of the mortar bars during ultrasonic measurements. Ultrasonic measurements were carried out on the mortar bars to assess the progressive damage induced by exposure to the strongly alkaline solution.

4 EXPERIMENTAL SETUP

The experimental setup for the ultrasonic testing procedure using the NWMS method is shown in Figure 1. Two signals with different frequencies were used in the nonlinear acoustic modulation method. One of the signals was a high frequency signal that was transmitted through the length of the mortar bars and received by the transducers. The second signal was a low frequency signal that was sent across the cross-section of the mortar bar. A function generator was used to generate the high frequency signal, a continuous sine wave at a frequency of 39 kHz. An instrumented impact hammer is used to produce a low frequency vibration, which normally was in the range of 0 to 10 kHz. This low frequency signal is acquired by an accelerometer, and any high frequency component in this signal was removed by a low-pass filter. Low frequency waves with different amplitudes, and hence different levels of energy, were produced in the mortar bar by varying the force of impact of an instrumented hammer on the mortar bar. Fifteen sets of such measurements with different amplitudes were taken for each mortar bar sample on each day. The test duration is ~20 minutes.

5 RESULTS AND DISCUSSION

The low and high frequency signals received by the accelerometer and the transmitted transducer respectively are shown in Figures 2 and 3. The frequency spectra of these time domain signals are shown in Figures 4 and 5. In Figure 5, sidebands are apparent on both sides of the nominal frequency (39 kHz). These sidebands correspond to the various resonant modes due to the impact of the hammer, which are captured by the accelerometer (Figure 4).

According to nonlinear acoustic theory, the amplitude of sidebands is proportional to the amplitudes of two incident signals and the nonlinearity parameter. Since ASR damage was induced in the specimens by exposure, it can be assumed that the nonlinearity observed may be related to the alkali reactivity of aggregates. Thus, the damaging effect of ASR in the mortar bar specimens, which causes nonlinear modulation of the two input waves, can be related to the ultrasonic results.

When the amplitude of the high frequency signal is fixed, the slope between the amplitude of the sideband and the low frequency impact signal will be proportional to the nonlinearity parameter (D). In this research, an integrated sideband amplitude in the effective frequency domain is used to calculate a representative nonlinearity parameter of the material at a given time. This result was called "energy" and is considered the measurement parameter. The integration of sideband amplitude is called "sideband energy" and the integration of the amplitude of the impact signal, the "impact energy." Figure 6 shows a typical energy relationship for a mortar sample that has undergone ASR. These data show that the "sideband energy" increases linearly with increasing "impact energy," which agrees very well with the theoretical prediction.

Initially, tests were conducted to validate the ability of the developed NWMS method to distinguish between ASR-damaged specimens and undamaged control specimens and to provide a measure of accumulated damage in the specimens experiencing ASR damage. The energy relations with respect to age for both damaged and control specimens are shown in Figures 7 and 8, respectively. These results show that the slope changes with time for the damaged specimens, whereas the slope remains nearly constant over time for the control specimens. The results clearly demonstrate that this nonlinear acoustic modulation technique can effectively differentiate between ASR-damaged specimens and undamaged specimens. Furthermore, the increasing slope of the energy relation for the

ASR-damaged specimens (Figure 7) with time (and increasing alkaline exposure and damage) demonstrates that this technique can be used to assess progressive ASR-induced damage in mortars.

The relationship between the ultrasonic parameter (here, the slope of the energy relationship) and exposure time up to 14 days is shown in Figure 9, for one of the aggregates examined. These data show a clear correlation between the slope of the energy relationship and the increasing exposure time in the mortar bars. The correlation further validates the potential of the nonlinear acoustic method for the assessment of ASR damage.

After demonstrating that the method can differentiate between damaged and undamaged mortars and that a relationship exists between the measured nonlinear parameter and the exposure time, further tests were carried out with three aggregates of varying reactivity. Accelerated mortar bar tests show that aggregate 1 is the most reactive, aggregate 2 is moderately reactive and aggregate 3 is the least reactive, with 14 day expansion values of 0.456%, 0.136% and 0.098% respectively. The expansion results of accelerated mortar bar tests are shown in Figure 10.

Figure 11 shows the slope of energy-exposure relationship for each of these three aggregates, up to 14 days. For all three aggregates, the slope-exposure relationship increases with accumulating ASR damage, but at different rates. For example, the increase in slope for the most reactive aggregate (1) is the highest, when compared to the slopes of the other less reactive aggregates. The slope of the nonlinear parameter for aggregate 2 was observed to increase at a faster rate than that for aggregate 3. It is proposed that this difference among the slopes qualitatively represents the known distinction in the alkali-reactivity of these three aggregates. These results indicate that this energy parameter derived from the NWMS ultrasonic tests, the energy slope, can also distinguish between aggregates of varying alkali-reactivity.

Comparing the data for the early exposure time for each of the three aggregates in Figure 11 also shows that the proposed NWMS ultrasonic test can distinguish between the aggregates of varying reactivity to ASR faster compared to the AMBT test. In the case of aggregate 1, with known high alkali reactivity, a significant increase in the energy slope was observed as early as one day of exposure to the alkaline solution. Aggregate 2, with moderate reactivity, showed considerable increase in the slope parameter within 4 days of exposure, whereas, relatively low-reactivity aggregate 3 showed a lesser increase in the energy parameter even at 6 days of exposure. Due to the clear distinction in the slopes of the energy parameter at early ages, alkali-silica reactivity of a particular aggregate can possibly be assessed as early as 4 days of exposure to the alkaline environment using the proposed NWMS ultrasonic test.

6 CONCLUSIONS

Building upon the nonlinear acoustic principle that increasing damage in a material, such as by alkali silica reaction in portland cement mortars, increases its nonlinear response, the developed nonlinear acoustic technique was examined as a potential ultra-accelerated test for screening of aggregates sources. The results show that this nonlinear acoustic modulation method can not only identify the existence of ASR damage in specimens, but also distinguish between aggregates with different alkali-reactivity. The variations in aggregate reactivity are apparent as early as 4 days of exposure during the nonlinear acoustic testing. It is proposed that the slope of the energy relationship, the adopted parameter based on ultrasonic tests, could be considered as a direct parameter associated with the reactivity of aggregates. The present work demonstrates that this nonlinear acoustic method is potentially a more rapid test, which could be used alone or in conjunction with standard methods.

ACKNOWLEDGEMENTS

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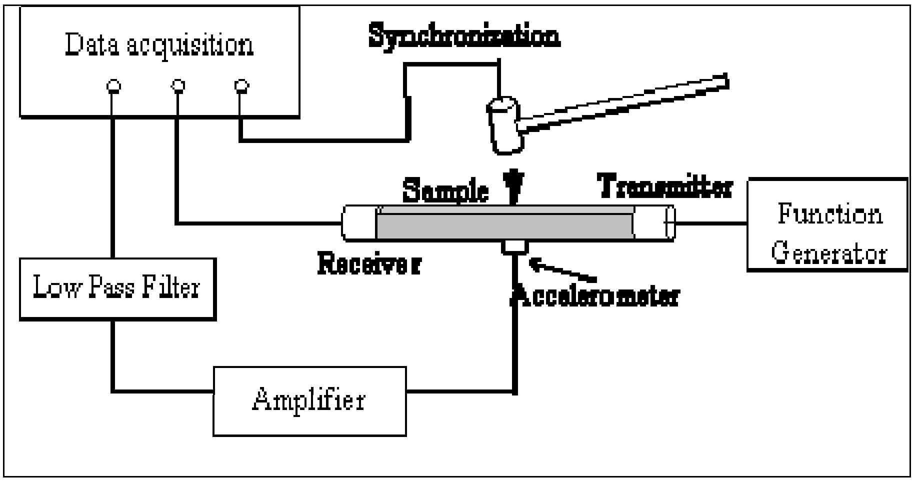

Figure 1. Schematic plot of experimental setup

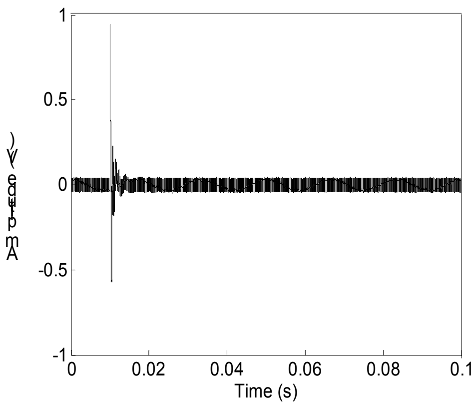

Figure 2. Modulated impact signal in time domain

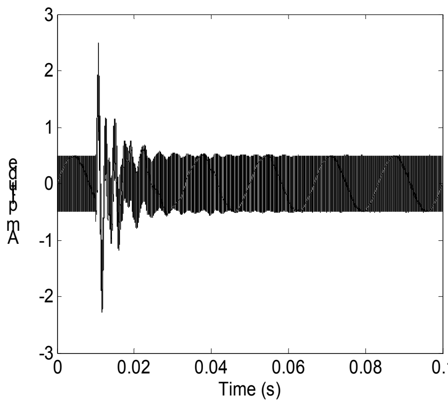

Figure 3. Modulated resultant signal in time domain

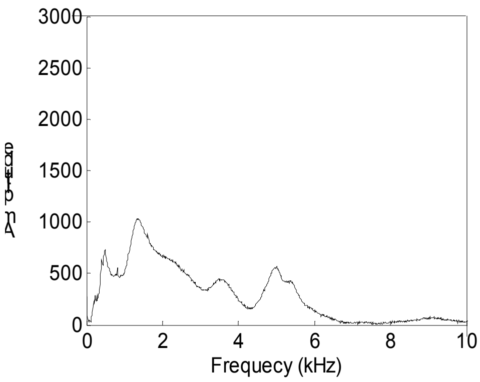

Figure 4. Spectrum of modulated impact signal

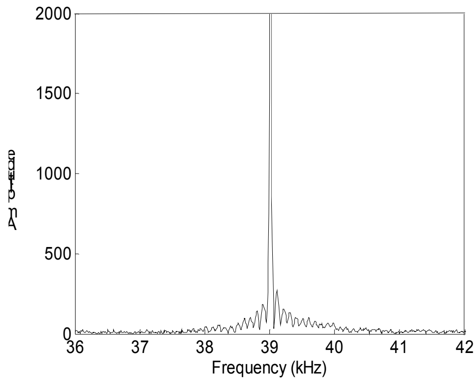

Figure 5. Spectrum of modulated resultant signal

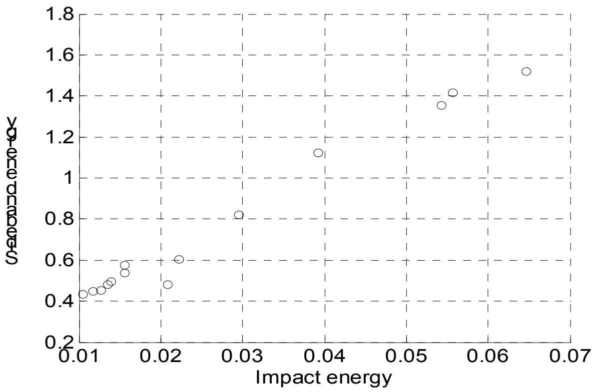

Figure 6. Linear relationship of sideband energy and impact energy

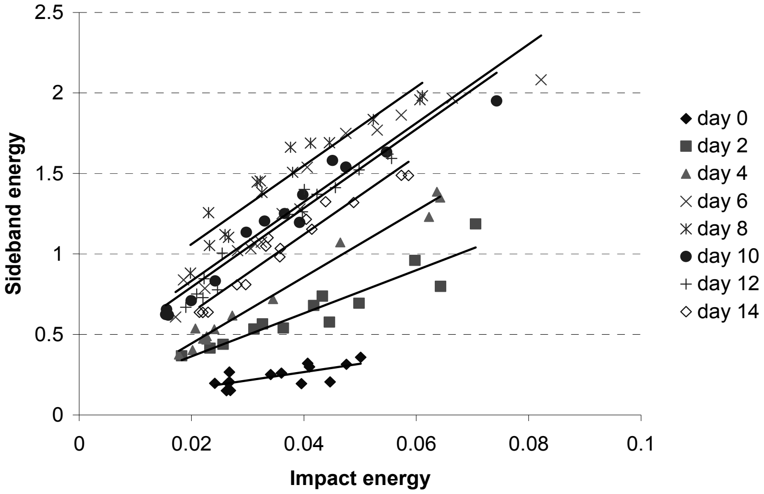

Figure 7. Energy relationship in a mortar bar undergoing progressive ASR damage, an initial measurement in the undamaged state at day 0 and a final measurement after 14 days soaking in 80°C 1 N NaOH solution.

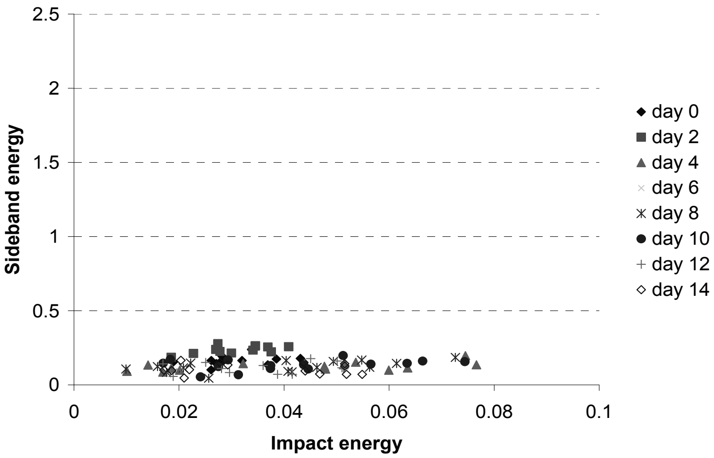

Figure 8. Energy relationship in the companion control sample (non-reactive aggregate), stored at 23°C and 50% relative humidity for a 14 day period.

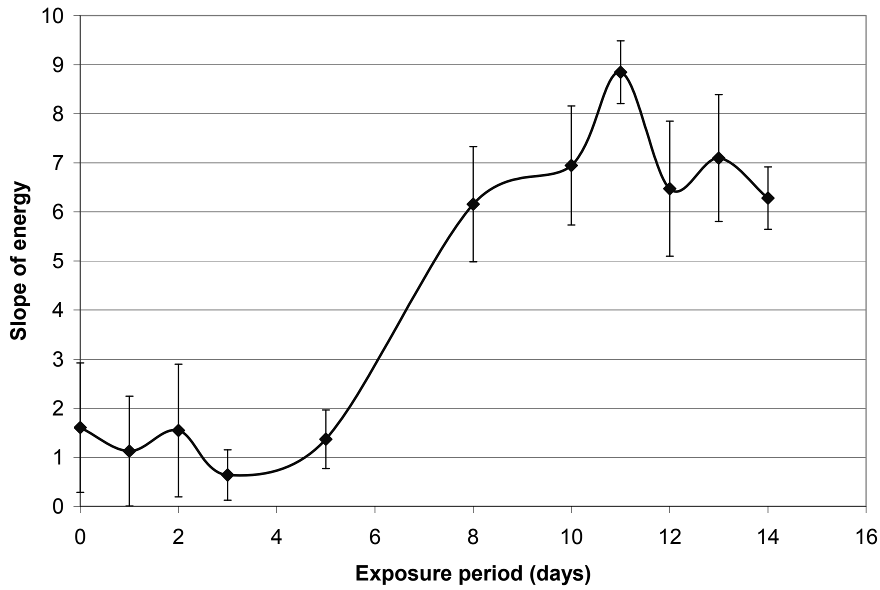

Figure 9. Relationship between slope of energy and exposure period (Aggregate 3). Standard deviation error bars for the slope of energy are also shown in the graph

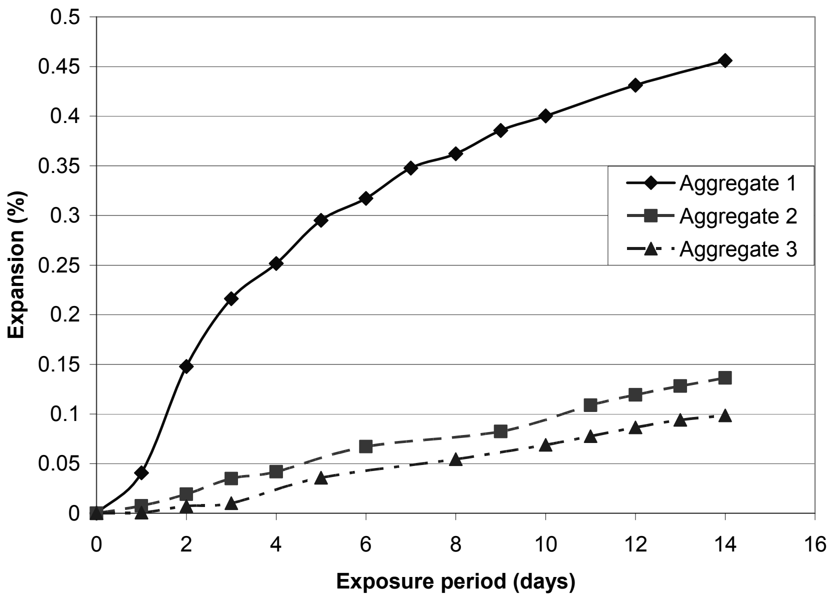

Figure 10. Expansion of three aggregates of varying reactivity over a 14-day exposure period

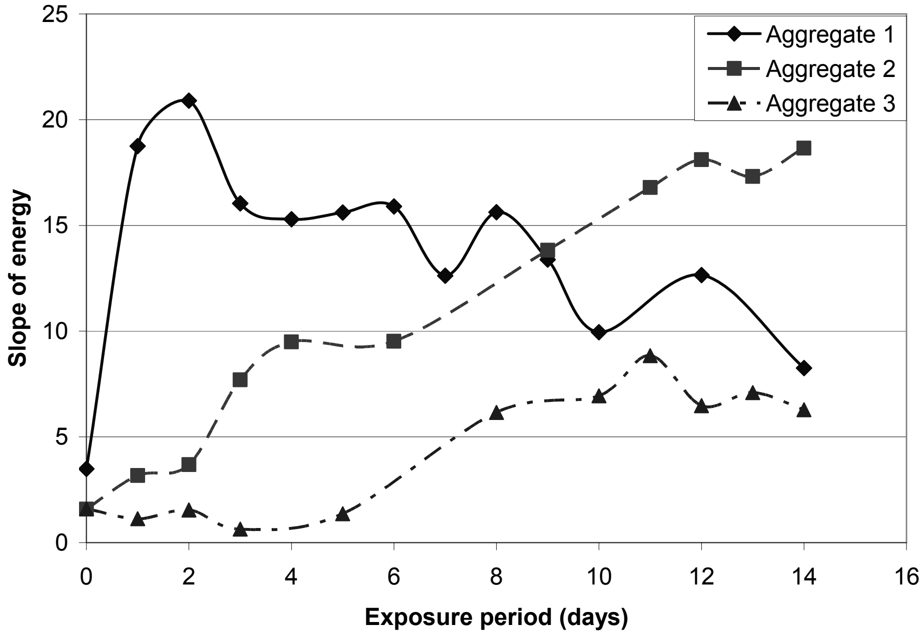

Figure 11. Correlation between slope of energy and alkali-reactivity of three aggregates of varying reactivity over a 14-day exposure period.