Cement and Concrete Composites 73 (2016) 123–135

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Detecting alkali-silica reaction: A multi-physics approach

Mehdi Rashidi [a], Marc C.L. Knapp [b], Ashkan Hashemi [c], Jin-Yeon Kim [a], Kristen M. Donnell [c], Reza Zoughi [c], Laurence J. Jacobs [a, d], Kimberly E. Kurtis [a, *]

[a] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA 30332, USA
[b] WDP & Associates Consulting Engineers, 10621 Gateway Blvd., Suite 200, Manassas, VA 20110, USA
[c] Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA
[d] G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, 813 Ferst Drive, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form
21 June 2016
Accepted 4 July 2016
Available online 7 July 2016

Keywords:
Alkali-aggregate reaction
Microwave
Nonlinear acoustics
Characterization
Expansion
Damage

ABSTRACT

A multi-physics approach for the assessment of alkali silica reaction (ASR) generates new foundational understanding of the nature of the reaction, which ultimately can be used for the development of techniques and tools for the assessment and monitoring of existing concrete structures. The approach combines two nondestructive evaluation techniques: (1) nonlinear acoustic measurements, which are sensitive to microcracking; and (2) microwave materials characterization measurements, which are sensitive to moisture including the transition of water from its free state in the pore solution to a bound state within accumulating ASR gel. Comparison with assessment of expansion and damage rating index obtained from petrographic analysis on standard mortar bars shows a correlation between all of the measures. Specifically, a strong correlation is found between the cumulative average nonlinearity parameter and expansion, and there is also agreement of the microwave measurements with the damage rating index.

1. Introduction

One of the most recognizable indications of the alkali-silica reaction (ASR) is gel exudation at the concrete surface [1,2]. Once the gel reaches the surface of a structure, however, extensive expansion and damage limit repair options and potentially deleterious materials may have been used in subsequent construction projects. Therefore, early detection of alkali-silica reaction occurring within concrete would be a significant contribution to the sustainability of concrete infrastructure.

The primary cause of deterioration associated with the ASR is the expansion of a characteristic gel that generates internal tensile stress and leads to microcracking. While it is understood that the gel forms from the reaction between aggregate containing amorphous or poorly crystalline siliceous minerals and the alkaline pore solution in concrete, the underlying mechanism of expansion and swelling pressure remains poorly understood [3–5]. Also, the relationship between the ASR gel composition, the volume of gel produced, and the potential for damage in concrete remain unresolved [3–7]. From a fundamental perspective, a comprehensive understanding of the relationships among gel composition, gel volume, gel expansion, and rate and extent of damage to concrete structures is critical for advancing the state of the art, and would have important implications for the screening of materials, the validation of mix designs, and the monitoring of concrete infrastructure.

Here, a multi-physics approach is used to provide a comprehensive study of ASR which aims to link chemical changes (i.e., transition of water from pore solution into ASR gel), physical changes (i.e., gel formation, microcracking) and mechanical properties (i.e., changes in material linear elasticity or increasing nonlinearity with increasing damage). This approach includes monitoring of progressive ASR damage and its relationship with water absorption using nonlinear acoustic and microwave nondestructive testing methods, with validation by standard expansion measurements and petrographic assessment.

In recent years, the nondestructive evaluation of ASR has developed significantly. For instance, Chen et al. [8] introduced an acoustic technique, the nonlinear impact resonance acoustic spectroscopy (NIRAS) method, to quantify material nonlinearity induced by ASR damage, demonstrating that nonlinear techniques are more sensitive to changes in microstructures than conventional

* Corresponding author.
E-mail address: kimberly.kurtis@ce.gatech.edu (K.E. Kurtis).

http://dx.doi.org/10.1016/j.cemconcomp.2016.07.001
0958-9465/

linear methods. Over time, several studies have applied linear and nonlinear ultrasonic techniques to quantify ASR damage in concrete [9–11] and to assess the potential reactivity of certain aggregate [8]. Ultimately, this research has led to the adoption of a provisional standard in AASHTO [12] for the screening of aggregate and concrete mix designs in conjunction with standard concrete prism testing (ASTM C1293 [13]).

While nonlinear acoustic methods are reliable for detecting microcracks [14–17] which may stem from a variety of sources in cement-based composites, such measurements cannot definitively detect ASR in concrete because they cannot directly detect the presence of ASR gel. In contrast, microwave measurements, which are sensitive to the amount of water and the chemical state of water in a material [18,19] have been applied to investigate the water-to-cement ratio and the progression of chloride ion ingress and quantifying defects in cement-based materials [18,20]. Recently, preliminary studies have demonstrated the potential for microwave measurements to distinguish between mortars containing alkali-silica reactive aggregate and those containing nonreactive aggregate [21,22], and mortars kept in different environmental conditions [23].

The current research explores the combination of emerging microwave materials characterization measurements with proven nonlinear acoustic measurements and verifies both nondestructive techniques against expansion and petrographic results. Relating the results from four distinct measures of ASR provides new knowledge about the connection between the formation of the ASR gel and the evolution of ASR damage.

2. Background

2.1. Microwave methods

Materials can be characterized by their intrinsic complex relative (to free-space) dielectric constant ε_r, as represented in Eq. (1) [24]:

$$\varepsilon_r = \varepsilon_r' + j\varepsilon_r'' \tag{1}$$

where ε_r', the relative permittivity, represents the ability of a material to store energy, and ε_r'', the relative loss factor, represents the ability of a material to absorb energy. Since the values of relative permittivity and loss factor are normalized to those of free-space (ε_o), they are dimensionless. By passing electromagnetic waves through a sample and measuring the reflected and transmitted energy, the dielectric properties of a material can be evaluated. In general, the dielectric properties of a consolidated material (i.e., concrete) are controlled by the dielectric properties of individual components, their relative proportions, and the physical and chemical properties of the material [25]. Dielectric properties are also frequency dependent, and certain frequencies of microwaves in particular are more sensitive to changes in the chemical composition of mortar and concrete. Based on previous work, microwave signals at the S-band frequency range (2.6–3.95 GHz) have shown high sensitivity to changes in mortars undergoing the alkali-silica reaction [21] and have been capable of distinguishing between the potentially reactive and nonreactive aggregate in the mortar samples by providing temporal data on the microstructural evolution [22]. In this research, S-band frequency range is used to assess mortars containing aggregate of varying reactivity at the end of accelerated mortar bar testing (AMBT) [26]. Differences in the reactivity of aggregate at the end of the test cause variations in the amounts of ASR gel, water content, and water state—bound or free water—in the mortars, which can be detected by differences in their dielectric properties. By combining data on dielectric properties with test methods that can detect the evolution of microcracking, a new test procedure that specifically detects ASR damage may be developed.

2.2. Nonlinear acoustic methods

Distributed microcracking caused by ASR can be detected by nonlinear acoustic methods [8,9,11,27]. While linear acoustic methods (e.g., ultrasonic pulse velocity method) detect macro-scale deficiencies [8–11,28,29], nonlinear acoustic methods are more sensitive to the presence of microcracks and therefore are better tools for detecting incipient ASR damage [8,9,11]. Nonlinear acoustic techniques have been used for the damage characterization of a variety of materials, whose nonlinear stress-strain relationship can be represented in Eq. (2) [30,31] as

$$\sigma = E_0\left[\varepsilon + \beta\varepsilon^2 + \delta\varepsilon^3 + \alpha\left\{\varepsilon(\Delta\varepsilon) + \frac{1}{2}\mathrm{sgn}(\dot{\varepsilon})\left(\varepsilon^2 - (\Delta\varepsilon)^2\right)\right\}\right] \tag{2}$$

Where σ is longitudinal stress, ε strain, E_0 the linear elastic modulus, β the quadratic nonlinearity parameter, δ the cubic nonlinearity parameter, α the parameter representing the material hysteresis nonlinearity, $\Delta\varepsilon$ the strain amplitude, $\dot{\varepsilon}$ the strain rate, and $\mathrm{sgn}(\dot{\varepsilon})$ the signum function where $\mathrm{sgn}(\dot{\varepsilon}) = 1$ if $\dot{\varepsilon} > 0$, $\mathrm{sgn}(\dot{\varepsilon}) = -1$ if $\dot{\varepsilon} < 0$, and $\mathrm{sgn}(\dot{\varepsilon}) = 0$ if $\dot{\varepsilon} = 0$. Since microcracking is the main cause of nonlinearity in cement-based materials, the hysteresis nonlinearity parameter (α) dominates the elastic nonlinearity parameters (β, δ) [31]. Therefore, the extent of damage or microcracking can be represented by the magnitude of hysteresis nonlinearity.

In standard mortar bars (such as those examined here) or in concrete prisms with hysteresis nonlinearity, the resonance frequency of a sample is the function of the excitation amplitude. As the excitation amplitude increases, the resonance frequency shifts to a lower value [11] and as damage progresses, the increase in the excitation amplitude causes a greater downward shift in the resonance frequency, which may be assessed using the nonlinear impact resonant acoustic spectroscopy (NIRAS) method [8,11,31–35], and the hysteresis nonlinearity can be evaluated according to Eq. (3), as

$$\frac{f_0 - f}{f_0} = \alpha' A \tag{3}$$

where f_0 is the linear resonant frequency of the sample, f the resonant frequency of the sample at the excitation level, α' directly proportional to the hysteresis nonlinearity parameter (α) and A the acceleration amplitude.

3. Experimental investigation

Standard mortar bars were prepared using three aggregate sources: two potentially reactive aggregate (Reactive-1 and Reactive-2) and one nonreactive aggregate (Non-Reactive). Samples were subjected to curing and exposure prescribed by the accelerated mortar bar test (AMBT) as in ASTM C1260 [26]. Subsequently, expansion, petrographic, microwave, and nonlinear acoustic assessments were performed on the samples. The sample exposure was consistent across all tests so that test results could be directly compared.

3.1. Materials and sample preparation

Based on the potential reactivity level as defined in ASTM C1260 [26] and field performance history, three sources of natural