INL/EXT-18-51461

Light Water Reactor Sustainability Program

Casting of Reinforced Concrete Beam: Project Progress

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September 2018

U.S. Department of Energy
Office of Nuclear Energy

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

Aging concrete structures in nuclear power plants undergo mechanical, physical, chemical, and radioactive degradation. One of the chemical degradation mechanisms currently being investigated under the Plant Modernization Pathway of the Light Water Reactor Sustainability Program is the alkali-silica reaction (ASR). The ASR is a chemical process that, over time, causes expansion of calcium silicate hydrate gel. To date, the research project has studied ASR gel formation and expansion in non-reinforced concrete specimens using the vibro-acoustic modulation (VAM) technique. However, nuclear plant concrete structures are reinforced, and effect of the reinforcement on application of VAM techniques is unknown.

To address this issue, a research activity was initiated between Idaho National Laboratory, Vanderbilt University, and University of Nebraska - Lincoln to study the impact of reinforcement in concrete structures on application of the VAM technique. In support of this activity, University of Nebraska - Lincoln is casting and curing four reinforced concrete samples that, at the end of the curing period, will be transferred to Vanderbilt University to perform an experimental VAM study. Vanderbilt University and Idaho National Laboratory will analyze the resulting data and enhance the developed structural health monitoring framework.

This report presents a summary of the progress to date on casting and curing of reinforced concrete samples at University of Nebraska – Lincoln.

ACKNOWLEDGMENTS

This report was made possible through funding by the United States Department of Energy's Light Water Reactor Sustainability Program. We are grateful to Alison Hahn of the United States Department of Energy and Bruce Hallbert and Craig A. Primer at Idaho National Laboratory for championing this effort.

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ACRONYMS

ASR	alkali-silica reaction
NaOH	sodium hydroxide
NDE	nondestructive examination
NPP	nuclear power plant
VAM	vibro-acoustic modulation

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1. INTRODUCTION

This project focuses on concrete structures in nuclear power plants (NPPs). Concrete structures are grouped into the following four categories: (1) primary containment, (2) containment internal structures, (3) secondary containment/reactor buildings, and (4) other structures such as used fuel pools, dry storage casks, and cooling towers. These concrete structures are affected by a variety of chemical, physical, and mechanical degradation mechanisms, such as the alkali-silica reaction (ASR), chloride penetration, sulfate attack, carbonation, freeze-thaw cycles, shrinkage, and mechanical loading (Naus 2007). Age-related deterioration of concrete results in evolving microstructural changes (e.g., slow hydration, crystallization of amorphous constituents, and reactions between cement paste and aggregates). Therefore, it is important that changes over long periods of time are measured and monitored, and their impacts on component integrity are analyzed in order to best support long-term operations and maintenance decisions.

Vanderbilt University, in collaboration with Idaho National Laboratory and Oak Ridge National Laboratory personnel, is developing a framework for health diagnosis and prognosis of aging concrete structures in NPPs that are subject to physical, chemical, and mechanical degradation (Mahadevan et al. 2014; Agarwal and Mahadevan 2014). The framework will allow researchers to assess concrete structure degradation by integrating the following four technical elements: (1) monitoring, (2) data analytics, (3) uncertainty quantification, and (4) prognosis. For details on each element of the proposed framework, refer to Mahadevan et al. (2014).

A research activity is initiated between Idaho National Laboratory, Vanderbilt University, and University of Nebraska - Lincoln to study the impact of reinforcement in concrete structures on application of the VAM technique. To support this activity, University of Nebraska - Lincoln is casting and curing four reinforced concrete samples that, at the end of the curing period, will be transferred to Vanderbilt University to perform an experimental VAM study. Vanderbilt University and Idaho National Laboratory will analyze the resulting data and enhance the developed structural health monitoring framework.

This report presents a summary of the progress to date on casting and curing of reinforced concrete samples at University of Nebraska – Lincoln.

2. TECHNICAL BACKGROUND

2.1 Concrete Structures Affected by Alkali-Silica Reaction

ASR is a reaction in concrete between alkali hydroxides (K+ and Na+) in the pore solution and reactive non-crystalline (amorphous) silica (S2+) found in many common aggregates, given sufficient moisture. This reaction occurs over time and causes expansion of the altered aggregate by the formation of a swelling gel of calcium silicate hydrate (C-S-H). The primary sources of reactive silica are reactive aggregates, while alkali is present in the cement clinker. ASR swelling results from the relative volume increase between the product and reactant phases involved in the chemical reaction. First, the products expand in pores and micro-cracks of the cementitious matrix. Once this free expansion space is filled, the swelling is restrained and the product phases exert local pressure on the surrounding concrete skeleton (Ulm 2000). Figure 1 depicts the mechanism of ASR (Kreitman 2011).

With the presence of water, the ASR gel increases in volume and exerts an expansive pressure inside the material, causing spalling micro- to macro-cracks (due to nonhomogeneous swelling related to non-uniform moisture distribution). As a result, ASR reduces stiffness and tensile strength of concrete - properties that are particularly sensitive to micro-cracking. ASR can also cause serious cracking in concrete, resulting in critical structural problems that can even force the demolition of a particular structure. The serviceability of concrete structures includes resistance to excessive deflections, as well as a host of other durability concerns that can shorten the service life of a structure. Large surface crack widths and deep penetration of open surface cracks promote the ingress moisture and any dissolved aggressive agents, such as chlorides. Additionally, loss of concrete stiffness and potential for reinforcement yield are a concern for concrete deflection capabilities.

ASR is a complex chemical phenomenon, the rate and extent of which depend upon a number of material and environmental parameters, and the interactions among parameters is not fully understood. Because ASR causes premature concrete deterioration, a method to perform quantitative assessment of ASR structural effects during service life (both in time and space) is needed. In particular, a combined experimental modeling investigation method is required to evaluate the impact of ASR on the dimensional stability of concrete structures. Although ASR has been identified as a cause of deterioration of numerous concrete structures, and research has yielded basic understanding of the mechanism of the reaction, knowledge of the structural effects of ASR and how to best assess the extent of damage to existing structures remain a major topic of ongoing research. This is because the expansion and cracking patterns (the most obvious signs of distress) caused by ASR can also be produced by other distress mechanisms (e.g., drying shrinkage and sulfate attack).

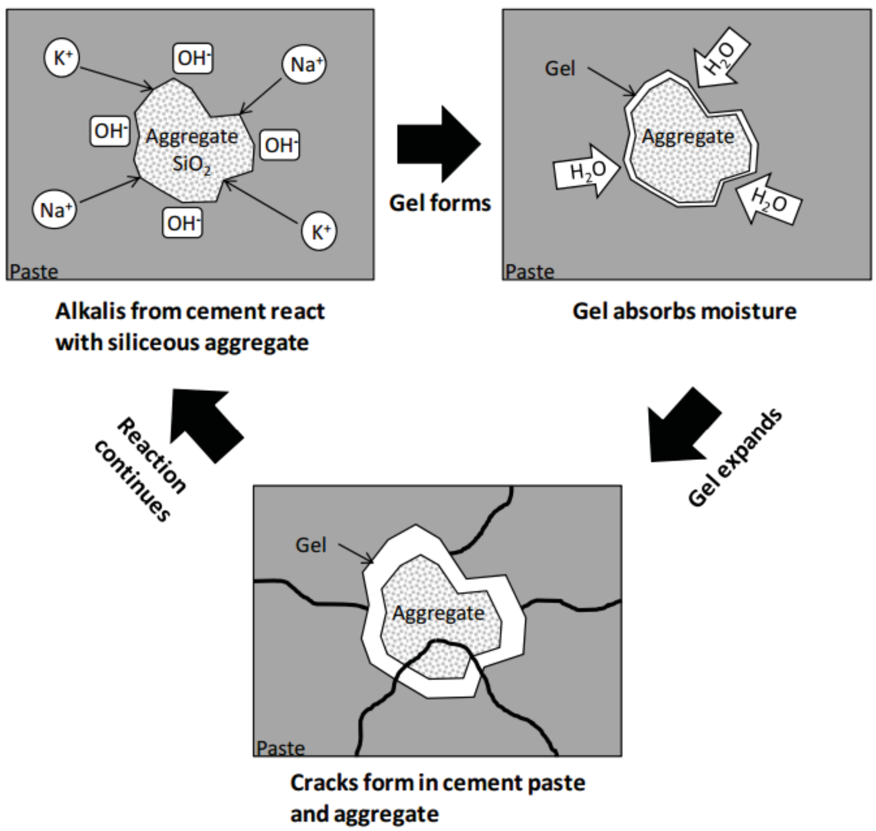

Figure 1. Mechanism of alkali-silica reaction (Kreitman 2011).

2.2 Vibro-Acoustic Modulation

VAM, also known as nonlinear wave modulation spectroscopy, is a nondestructive examination (NDE) technique that relies on detecting the dynamic signature of nonlinear structural behavior as the primary indicator of damage. Specifically, VAM aims at detection of modulation of a higher frequency by a lower frequency caused by delamination or cracks in structural components. The utility of VAM for detecting debonding flaws and cracks in composites and metals, as well as ASR-induced cracks in concrete (Chen et al. 2008, 2009), has been demonstrated in the past.

In the VAM technique, the structural component of interest is excited simultaneously using a combination of two signals of specific frequencies, and the dynamic response is measured at various locations using acoustic sensors (accelerometers). The low-frequency input is termed the "pump," and the high-frequency input is termed the "probe" (Kim et al. 2014). A geometric or material nonlinearity–in the form of variable contact area, nonlinear adhesive bond at the surfaces of a crack, or delamination–causes modulation of the probing frequency by the pumping frequency. This modulation, and hence the presence of the flaw, can be seen in the frequency spectra of the measured response as peaks of higher magnitude (sidebands) around the probe frequency. The interaction of these signals at different frequencies is used to understand the nonlinear stress-strain relationship in the structure of interest. For example, Figure 2 shows the response when the two excitation signals are theoretically applied to a structure. If the structure is linear and damped (i.e., undamaged), the response in the steady state is the linear superposition of the responses of each signal, and only the linear components of Figure 2 will appear in the frequency spectrum of the response. Damage in a structure introduces nonlinearity and, as a result, the response contains both the probing frequency and the pumping frequency in addition to other frequency components such as harmonics of each signal and sidebands around the probing signal.

Most previous work on VAM testing has focused on detection of damage based on the presence of sidebands in the spectrum of the dynamic response of the structure. Recently, Singh et al. 2017 showed that VAM testing can be used for damage localization or damage mapping. They hypothesized that the effect of nonlinearities (geometric or material) is pronounced near the location of the flaw, and therefore the relative magnitude of a damage index based on sideband size may enable localization of the flaw. That is, if a spatial distribution showing the variation of the damage index is obtained using a sensor grid, the damage is located in the neighborhood of sensors exhibiting the highest damage index. They tested their hypothesis using numerical simulations of VAM in delaminated composite plates. They studied damage indices based on various characteristics of spectrum of the dynamic response of the plate (magnitude of sidebands, probe frequency, pump frequency) and established the feasibility of VAM-based damage localization. Thus, the utility of the damage mapping scheme has been studied for homogeneous, anisotropic, thin composite plates by performing numerical experiments. However, the applicability of VAM-based damage mapping to detect and localize cracks in structural concrete components has not been investigated. We remark that thick, heterogeneous structural concrete components present significant challenges for VAM test setup, data analytics, and damage mapping.

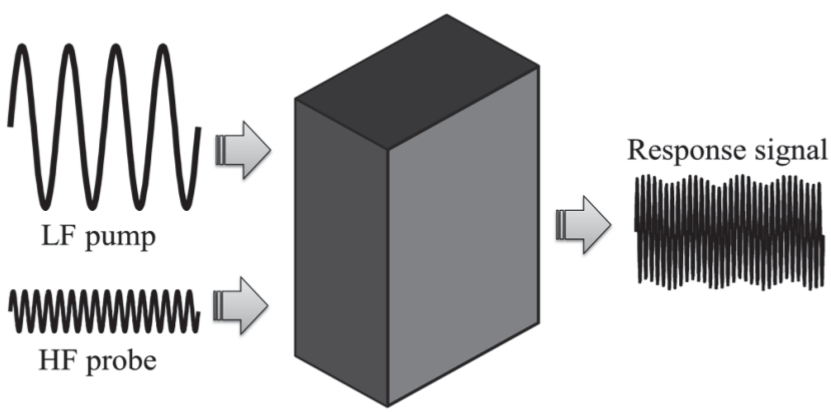

Figure 2. The principal of the VAM technique (Kim et al. 2014).

3. REINFORCED CONCRETE SAMPLES

Previous Vanderbilt work has developed the vibro-acoustic technique for detection and localization of ASR-related damage in concrete structures, using non-reinforced concrete slab samples of sizes (2 ft. x 2 ft. x 0.5 ft.) and (2 ft. x 1 ft. x 1 ft.). This task will investigate the application of this methodology to reinforced concrete, representative of the concrete structures found in nuclear power plants. The following four sub-tasks have been established:

1. Casting of 4 reinforced concrete specimens to simulate ASR damage
2. Preliminary expansion measurements
3. Vibro-acoustic modulation (VAM) testing
4. Data analytics for damage diagnosis

Subtasks 1 and 2 will be performed by University of Nebraska, Lincoln (UNL), under the direction of Prof. Jinying Zhu. Four reinforced concrete specimens will be cast and cured under aggressive conditions. The four samples are all of dimension 1 ft. x 1 ft. x 2 ft. and consist of one unreinforced control sample with non-reactive aggregate, one unreinforced sample with Gold Hill reactive aggregate, one transverse-reinforced sample with Gold Hill reactive aggregate, and one bidirectionally reinforced sample with Gold Hill reactive aggregate. Table 1 presents the casting date and Figures 3 and 4 are controlled sample and bidirectional reinforced sample in environmental chamber. Reinforced concrete samples with transverse direction confinement and reactive aggregate concrete sample without confinement will go into the environmental chamber in October.

The samples will be cured and conditioned in an environmental chamber at UNL at a temperature of 38^{o}C and relative humidity > 95%. The UNL team will install stainless steel targets on sample surfaces to monitor concrete expansion during curing and conditioning using demountable mechanical strain gauge devices (150 mm and 500 mm gauge lengths). This expansion data will be shared with the Vanderbilt team. Once the conditioning is complete, the samples will be shipped to Vanderbilt University.

Table 1: Concrete samples and their casting date

Concrete Samples	Casted Date
Non-reactive aggregate reinforced sample (Control Sample)	8/28
Reactive aggregate reinforced sample (no confinement)	9/27
Reactive aggregate reinforced sample (transverse confinement)	9/27
Reactive aggregate reinforced sample (bidirectional confinement)	9/20

Figure 3. Non-reactive aggregate reinforced concrete sample (control sample).

Figure 4. Reactive aggregate reinforced concrete sample with bidirectional confinement.

Subtask 3 will be performed by Vanderbilt University personnel, under the direction of Prof. Sankaran Mahadevan. VAM tests will be conducted on the four samples at regular intervals to detect, diagnose and monitor the ASR-related damage. The tests will consist of excitation at two frequencies (high and low) and measurement of the dynamic response at multiple locations using accelerometers. During the curing period, Vanderbilt personnel will travel to UNL to conduct VAM tests. After the four slabs are shipped to Vanderbilt, VAM tests will be continued to monitor the damage progression.

Subtask 4 will be performed jointly by Vanderbilt University and Idaho National Laboratory. Data analysis results will be used to enhance the concrete structure health monitoring framework and provide insight into the application of VAM techniques to the large-scale reinforced concrete structures that are found in nuclear plants.

4. SUMMARY

A research activity has been initiated between Idaho National Laboratory, Vanderbilt University, and University of Nebraska - Lincoln that will study the impact of reinforcement in concrete structures on the application of the VAM technique. To support this activity, University of Nebraska - Lincoln is casting and curing four reinforced concrete samples that at the end of the curing period will be transferred to Vanderbilt University to perform experimental VAM tests. Vanderbilt University and Idaho National Laboratory will perform the data analysis and enhance the developed structural health monitoring framework.

At the time of this report, University of Nebraska – Lincoln has casted all four concrete samples with two samples placed in an environmental chamber while other two to be placed in first week of October 2018.

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