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Light Water Reactor Sustainability Program

Digital Image Correlation of Concrete Slab at University of Tennessee, Knoxville

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ABSTRACT

Assessment and management of aging concrete structures in nuclear power plants require a more systematic approach than simple reliance on existing code margins of safety. Some degradation mechanisms of concrete manifest themselves via swelling or by other shape deformation of the concrete. Specifically, degradation of concrete structures damaged by the alkali-silica reaction (ASR) is viewed as one of the dominant factors impacting the structural integrity of aging nuclear power plants. Structural health monitoring of concrete structures aims to understand the current health condition of a structure based on heterogeneous measurements to produce high-confidence actionable information regarding structural integrity that supports operational and maintenance decisions.

Numerous nondestructive examination techniques (i.e., thermography, digital image correlation, mechanical deformation measurements, nonlinear impact resonance [DIC] acoustic spectroscopy, and vibro-acoustic modulation) are used to detect the damage caused by the ASR. DIC techniques have been increasing in popularity, especially in micro- and nano-scale mechanical testing applications due to its relative ease of implementation and use. Advances in computer technology and digital cameras help this method moving forward. To ensure the best outcome of the DIC system, important factors in the experiment are identified. They include standoff distance, speckle size, speckle pattern, and durable paint. These optimal experimental options are selected basing on a thorough investigation. The resulting DIC deformation map indicates that this technique can be used to generate data related to the degradation assessment of concrete structure damaged by the impact of the ASR.

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ACRONYMS

ASR	alkali-silica reaction
ASTM	American Society for Testing and Materials
DIC	digital image correlation
NaOH	sodium hydroxide
NDE	nondestructive examination
NPP	nuclear power plant

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INTRODUCTION

This project focuses on concrete structures in nuclear power plants (NPPs). The 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 a alkali-silica reaction (ASR), chloride penetration, sulfate attack, carbonation, freeze-thaw cycles, shrinkage, and mechanical loading (Naus 2007). The age-related deterioration of concrete results in continuing 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 integrity of the components are analyzed 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 investigate 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). The framework will enable plant operators to make risk-informed decisions on structural integrity, remaining useful life, and performance of the concrete structure. The demonstration examples performed at Vanderbilt University using various techniques to assess the ASR degradation in controlled concrete specimens were reported in Mahadevan et al. (2016).

The objective of this report is to examine the usage of digital image correlation (DIC) techniques in assessing the effect of the ASR on the integrity of concrete structures, which are exposed to the accelerated aging conditions in a laboratory. DIC is an optical nondestructive examination (NDE) technique that allows it to be used as a screening method for detecting surface defects, such as cracks, micro-cracks, and spalling. DIC is also capable of measuring deformation, displacement, and strain of a structure (Bruck 2012). Vanderbilt University performs the DIC on an ASR mockup concrete slab at the University of Tennessee, Knoxville. Preliminary results of this activity are documented here.

TECHNICAL BACKGROUND

Concrete Structures Affected by Alkali-Silica Reaction

The ASR is a reaction in concrete between the alkali hydroxides (K+ and Na+) in the pore solution and the reactive non-crystalline (amorphous) silica (S2+) found in many common aggregates, given sufficient moisture. This reaction occurs over time and causes the expansion of the altered aggregate by the formation of a swelling gel of calcium silicate hydrate (C-S-H). Reactive silica is mainly provided by reactive aggregates and the alkalis by the cement clinker. The 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 locally a pressure on the surrounding concrete skeleton (Ulm 2000). Figure 1 depicts the mechanism of the ASR (Kreitman 2011).

With water presence, 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, the ASR reduces stiffness and tensile strength of concrete because these properties are particularly sensitive to micro-cracking. The ASR also can 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 the 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, the loss of concrete stiffness and potential for reinforcement yield are a concern for concrete deflection capabilities.

The 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. This critical nature of the ASR on premature concrete deterioration requires the quantitative assessment of the ASR structural effects during service life (both in time and space). In particular, a combined experimental modeling investigation method is required to evaluate the impact of the ASR on the dimensional stability of concrete structures. Although the ASR has been identified as a cause of deterioration of numerous concrete structures and research has yielded more or less understanding of the mechanism of the reaction, knowledge of the structural effects of the ASR and how to best assess the extent of damage to existing structures remains a major topic of ongoing research. This is because the expansion and cracking patterns (most obvious sign of distress) caused by the ASR affect both the concrete and the reinforcing steel, but there are similar crack patterns can also be produced by other distress mechanisms (i.e., drying shrinkage and sulfate attack).

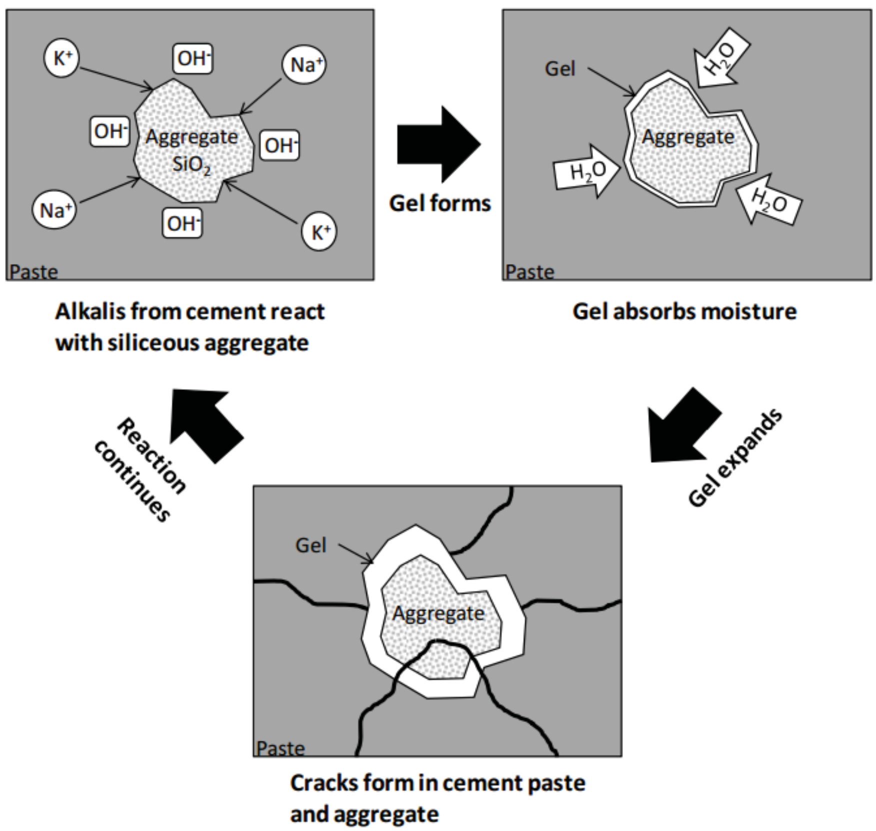


Figure 1. Mechanism of alkali-silica reaction (Kreitman 2011).

Digital Image Correlation: Nondestructive Examination Method for Structure Deformation Detection

NDE techniques are essential for assessing the ASR development in in-service concrete structures, such as in NPPs. For monitoring the ASR progression, the optical, thermal, acoustic, and radiation-based techniques are used for full-field imaging. Examples of these techniques include digital image correlation (DIC), infrared imaging, velocimetry, ultrasonic, and x-ray tomography. A particular consideration is the linkage of chemical degradation mechanisms to the observed degradation, which requires synergy between monitoring and prognosis. The standard test methods for determining the potential alkali-silica reactivity and for determination of length change of concrete due to an ASR are documented in American Society for Testing and Materials (ASTM) C1567-13 and ASTM C1293-08b, respectively.

DIC is a three-dimensional, full-field, and NDE optical technique to measure contour, deformation, vibration, and strain on almost any material (Bruck et al. 2012). The technique can be used for many tests including tensile, torsion, bending, and combined loading for both static and dynamics applications. The sketch of a typical three-dimensional digital image correlation system is presented in Figure 2 (Hagara et al. 2013)

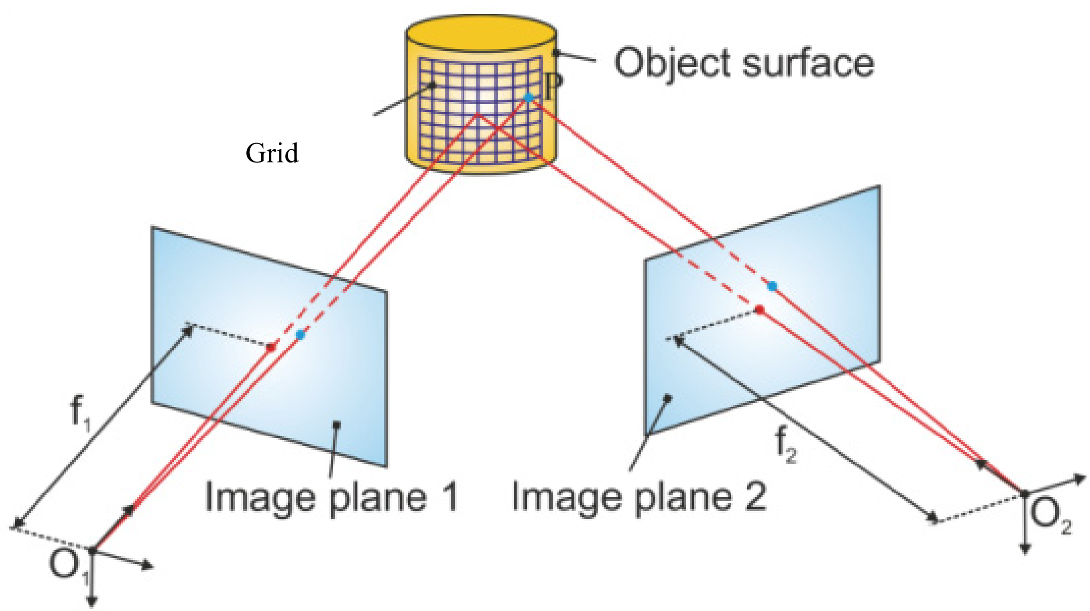


Figure 2. Stereoscopically located cameras of a three-dimensional digital image correlation system (Hagara et al. 2014).

The three-dimensional DIC procedure includes following steps:

1. Preparation:
   - Two cameras are mounted at either end of a tripod camera (base) bar so the relative position and orientation of the two cameras with respect to each other is known (O_1 and O_2 in Figure 2).
   - A random or regular pattern with good contrast is applied to the surface of the test object.
   - The initial imaging processing defines unique correlation areas, known as facets, that are defined across the entire imaging area (grid on object surface in Figure 2) and which typically range in size from 5 to 20 square pixels (McGinnis 2005).

2. Data acquisition and processing:
   - An image correlation algorithm tracks the movement of these facets by utilizing mathematical methods to maximize the similarity measures from successive images.
   - The three-dimensional locations of each facet can be calculated. Full-field displacement data can be obtained by tracking these measurement facet points within the applied random (or regular) target pattern.
3. Results:
   - Out-of-plane displacement (or deformation) map for the entire surface for each point in time as shown in Figure 3, when the measurements are taken.
   - Progression of expansion or relaxation of structure affected by various degradation mechanisms including the ASR, which can be calculated using the displacement maps taken at different times during the testing period or long term operation.

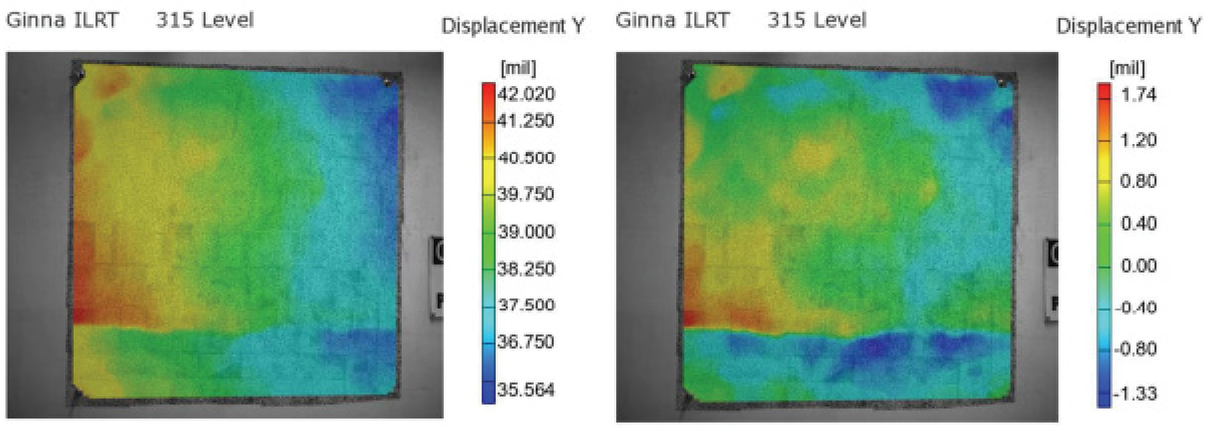


Figure 3. Vertical displacement map at two points in time.

DIC techniques have been increasing in popularity, especially in micro- and nano-scale mechanical testing applications due to its relative ease of implementation and use. Advances in computer technology and digital cameras have been the aiding technologies for this method. During routine pressure tests on containment vessels in NPP, when the internal pressure reaches 60 psi, it might be possible to use DIC to determine deformation of the concrete containment. DIC is capable of detecting surface defects such as cracks, micro-cracks, and spalling, but is unable to detect any subsurface defects. The primary benefit of DIC is in measuring deformation; therefore, its ability to detect changes in the dimensions of the slab due to the ASR gel expansion is of interest in this study. The DIC technique requires a speckled pattern on the specimen to anchor observations at different time instants, which makes it unsuitable for the small brick specimens that are immersed in sodium hydroxide (NaOH) solution or water. This is because the required pattern is disturbed and partly dissolved in the NaOH solution. In addition, DIC is only capable of detecting surface defects such as cracks, micro-cracks, and spalling, but it is unable to detect any subsurface defects. A three-dimensional strain field will give more insight than a linear measurement into how internal stresses affect the direction of the ASR-induced expansion.

EXPERIMENTAL STUDY

This research investigates the monitoring of degradation in concrete due to an ASR using the DIC techniques. Vanderbilt University began performing digital image correlation in late August on an ASR mockup concrete slab at the University of Tennessee, Knoxville. Three slabs have been cast and are to be studied with a variety of monitoring techniques, and the progression of the ASR will be studied over 3 years. The black-background-white-speckle pattern using acrylic latex paint (Sample b) is selected and applied to the slab casted at University of Tennessee, Knoxville. At the same time, the supporting fixtures for the DIC camera were also installed inside the environmental chamber. Technical basics for selecting optimal experimental settings are detailed in following subsection.

Experiment Configuration and Settings

Three slabs have been cast for studying a number of monitoring techniques to detect the progression of the ASR during a 3-year period. One of them was allocated for monitoring using DIC, which has 2 ft × 2 ft top surface. The side view of the slab inside an environmental chamber is shown in Figure 4. For DIC monitoring effort, a preliminary study was performed to determine the optimal speckle size and pattern; and identify the most durable paints.

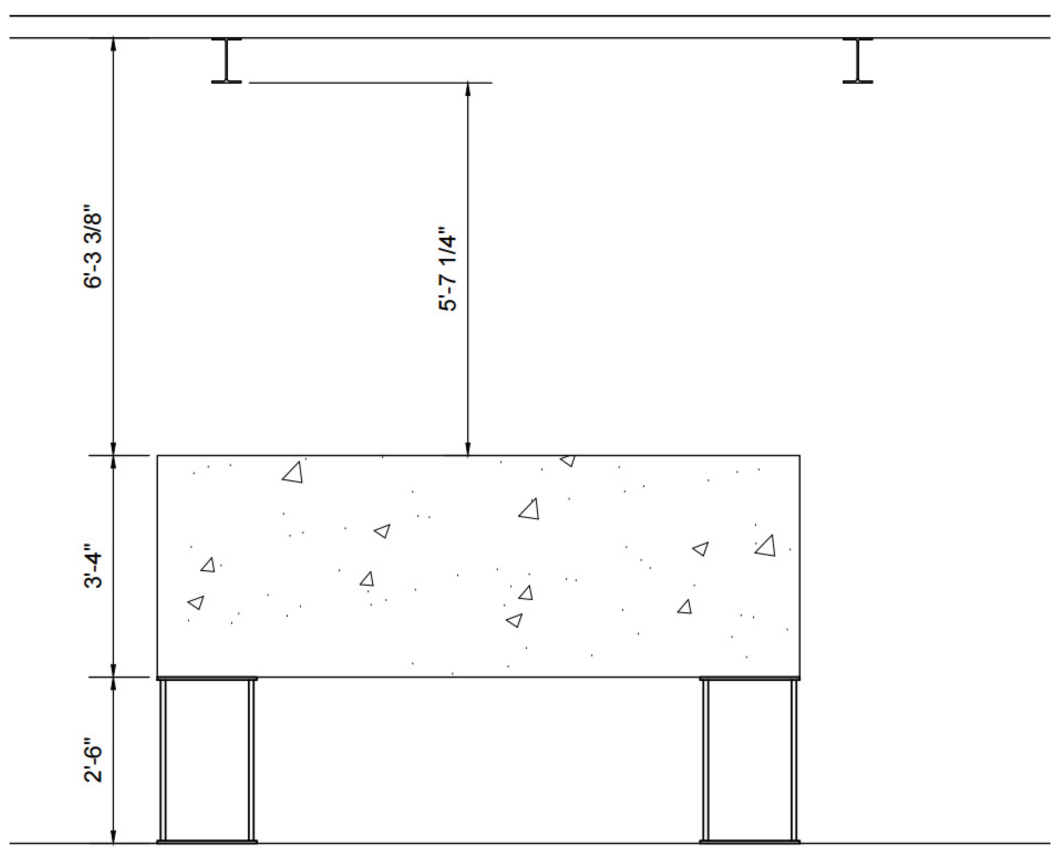


Figure 4. Side view of the slab in an environmental chamber for ASR research at the University of Tennessee.

Standoff Distance

Figure 4 shows that there is a slightly more than 5.5-ft clearance between the top of the slab and the I-beam supporting the environmental chamber. A fixture will be attached to the two I-beams to hold the DIC camera. As a result, the standoff distance can be conservatively estimated within the range between 4 ft and 4.5 ft, depending on the size of the fixture. The standoff distance of 4.22 ft, which gives a field of view area of 3.28 ft × 2.40 ft is selected to satisfy the required minimum area of 2 ft × 2 ft, according to the operation manual for the DIC system. In turn, the selected standoff distance is used in developing an appropriate speckle pattern. The 4.22-feet standoff distance is used for this study.

Optimal Speckle Size

The ARAMIS software requires a minimum speckle size of 5 pixels (Pickerd 2013). Given the selected standoff distance of 4.22 feet, the minimum speckle size is approximately 1 square millimeter. In addition to the size of the speckle, the software requires a specified facet size, which should satisfy the density requirements of speckles on the test specimen and resolution of the calculated strain field. Each facet must contain at least one speckle. A larger facet size would lower the resolution of the calculated strain field, but would reduce number of required speckles. The 15 × 15 pixel square speckle is selected to give the optimal resolution of calculated strain field and the necessary density of speckles on the test specimen.

Optimal Speckle Patterns

Six different speckle patterns shown in Figure 5 were tested. Speckle pattern (a) was created using a roller. Speckle patterns (b) – (f) were generated using spray paint. The nozzle position and angle of the spray can were varied to create different size and densities of speckles. The speckle pattern (b) was found to be the best option because of the optimum speckle size and density.

In addition, the paint durability study also found that using the white background color and the black painted speckles creates a higher contrast than the other way around, as shown in Figure 6. Sample (b) (on the right of Figure 6, which has white background with black speckles) produces higher contrast than Sample (a), which has black background with white speckles.

Durable paint

Finding a paint that will adhere to concrete for 3 years in a moist environment of the chamber is a substantial challenging task. There are two types of paint can be used: oil-based and acrylic latex. Commonly, the oil-based spray paint is used for DIC due to convenience. However, oil-based paint can react with the high alkalinity in cement causing debonding of the paint surface and trapping any moisture within the concrete under the paint surface (The Family Handyman 2016). During the 3-year testing period, the slab of interest will be housed in an environmental chamber with almost 100% relative humidity most of the time, except for a few short times the slab surface become dry when the humidity is turned down for nondestructive testing. This leads to some moisture being trapped underneath the paint surface, which will adversely impact the DIC results. An alternative to oil-based paints is acrylic latex paints, which allow moisture passage. To test the performance of acrylic latex paint, the Krylon Eco-Guard latex spray paint was applied to a concrete sample and placed under accelerated curing conditions (i.e., almost 100% relative humidity at 60°C) at Vanderbilt's Laboratory for Systems Integrity and Reliability. The acrylic latex paint showed no debonding or cracking on the surface of the tested slab after being exposed for 3 weeks to the accelerated curing conditions. Figure 6 show the durability test results of oil-based (a) and acrylic latex and (b) spray paints on concrete surface. Sample (a) surface shows debonding area of paint surface while Sample (b) paint surface looks intact.

As a result, the acrylic latex paint (Sample [b]) on the right of Figure 6) was selected for use in the assessment of DIC monitoring technique.

Installation of Speckle Pattern and DIC on the University of Tennessee Knoxville Slab

The black-background-white-speckle pattern using acrylic latex paint (Sample b) is selected and applied to the slab casted at University of Tennessee, Knoxville during the third week of August as shown in Figure 7. This slab is used for the DIC monitoring study. At that time, the support fixtures for the DIC camera were installed inside the environmental chamber as shown in Figure 8.

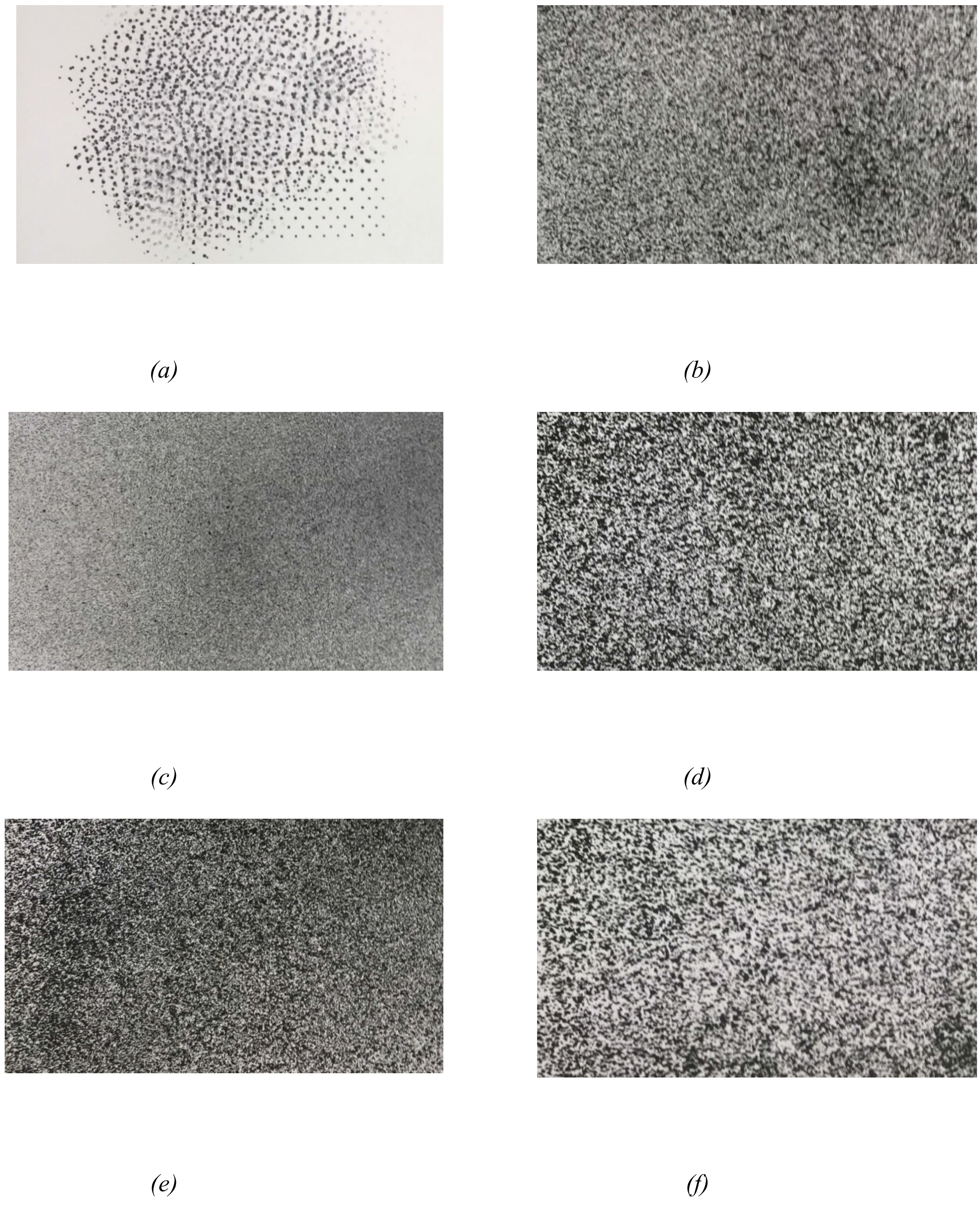
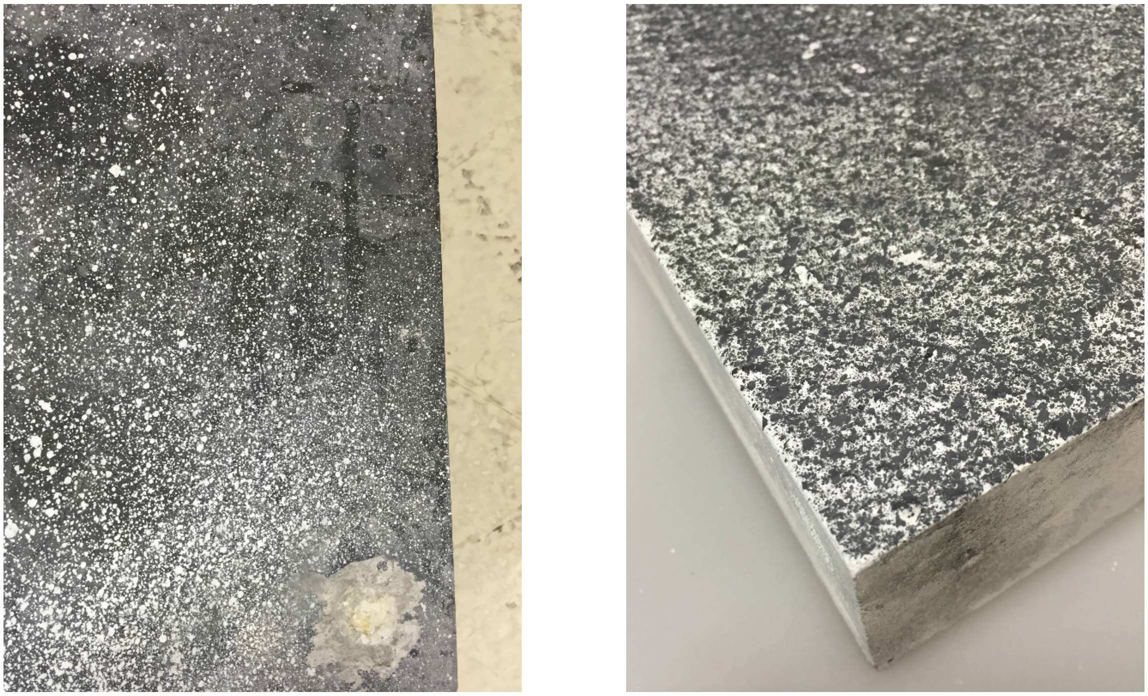


Figure 5. Available speckle patterns used for DIC study.



(a) (b)

Figure 6. Durability test results of oil-based (a) and acrylic latex (b) spray paints on concrete surface.

Figure 7. Speckle pattern painted on the 2 ft × 2 ft area of the University of Tennessee Knoxville Slab.

Figure 8. DIC camera support installation over the area of interest.

Deformation Map from Digital Image Correlation System

From multiple plane images taken by the DIC cameras, a three-dimensional strain field is calculated and compared to point measurements using mechanical calipers. The three -dimensional strain field will give more insight into how internal stresses affect the direction of the ASR-induced expansion than the linear point measurement. Figure 9 shows the out-of-plane deformation map of a specimen calculated by the DIC system using data collected from the selected speckle pattern (Pattern [b] in Figure 5), where the structure on which the speckle pattern was applied is buckled. This calculated deformation map in the out-of-plane direction has high spatial resolution due to successful selection of the DIC experiment settings. Some observed missing data around the perimeter of the deformation map are caused by those facets, which are extended outside the area of the speckle pattern. These missing data around the perimeter of the specimen will always occur regardless of what speckle pattern was chosen. The color-coded deformation map represents the uneven texture of the slab surface relative to a particular plane. According to this deformation map, the tested slab surface varies within the range from -2.88 to 10.54 mm around an initial flat surface as the result of structure swelling caused by the ASR gel.

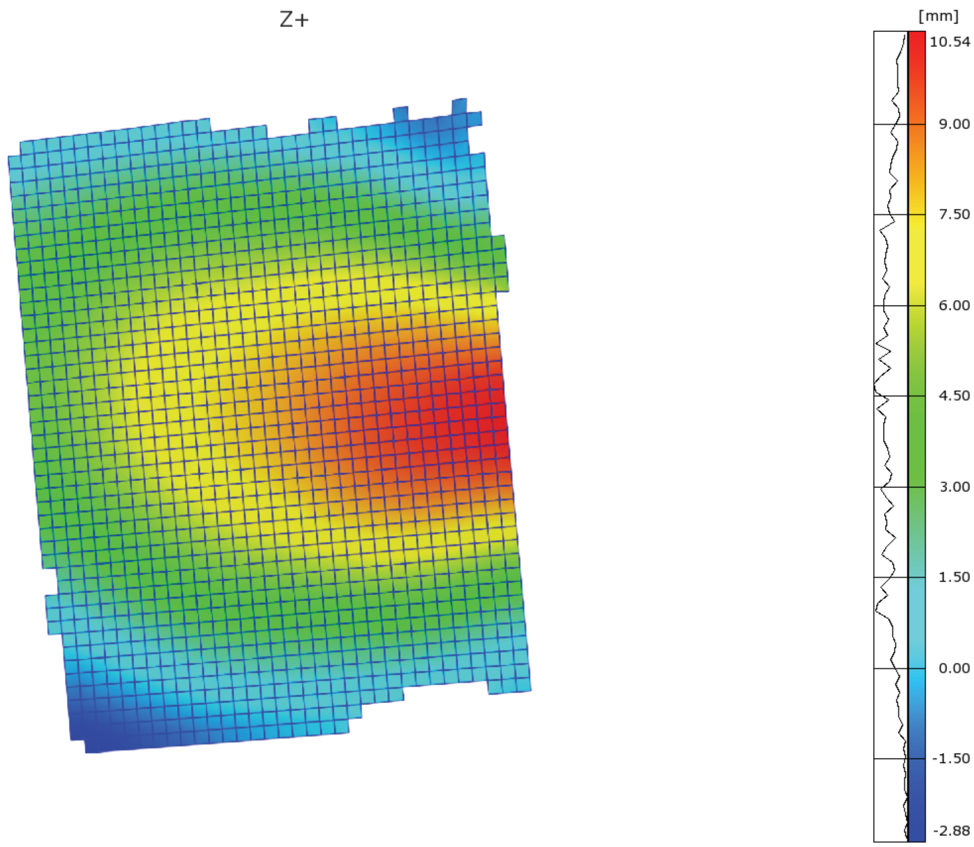


Figure 9. Out-of-plane deformation of a specimen produced by the DIC system.

CONCLUSION AND FUTURE RESEARCH

This document described the study of the usage of DIC techniques when assessing the effect of the ASR on the integrity of concrete structures after being exposed to the accelerated aging conditions in a laboratory setting. The optimal configuration for the University of Tennessee DIC experiment is defined as follows:

- *Standoff distance*: 4.22-feet standoff distance is estimated from sizes of the DIC environmental chamber.
- *Optimal speckle size*: 15 × 15-pixel square speckle is selected to give the optimal resolution of calculated strain field and the necessary density of speckles on the test specimen given the 4.22-feet standoff distance.
- *Speckle pattern*: black-background-white-speckle regular pattern.
- *Paint*: acrylic latex spray paint.

The DIC deformation map indicates that this technique can be used to generate data related to degradation assessment of concrete structure damaged by the impact of the ASR. Overall, this research focuses on data analysis, which can be used to support the development of diagnostic and prognostics models that will support continuous assessment of concrete performance. The resulting comprehensive approach will facilitate the development of a quantitative, risk-informed framework that could be generalized for a variety of concrete structures and be adapted for other passive structures. Future work will investigate the methods to incorporate the DIC data for assessing the impact of the ASR on realistic structures and in damage scenarios.

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