U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-####
NISTIR 7937

Alkali-Silica Reaction Degradation of Nuclear Power Plant Concrete Structures: A Scoping Study

Prepared by:

K.A. Snyder
H.S. Lew

National Institute of Standards and Technology
Engineering Laboratory
100 Bureau Drive
Gaithersburg, MD 20899

Manuscript Completed: March 2013
Date Published: April 2013

Jacob Philip, NRC Program Manager

NRC Job Code: V 6367

Office of Nuclear Regulatory Research

National Institute of Standards and Technology
U.S. Department of Commerce

NISTIR 7937

Alkali-Silica Reaction Degradation of Nuclear Power Plant Concrete Structures: A Scoping Study

K.A. Snyder
H.S. Lew
Materials and Structural Systems Division
Engineering Laboratory

March 2013

U.S. Department of Commerce
Rebecca Blank, Acting Secretary

National Institute of Standards and Technology
Patrick D. Gallagher, Under Secretary of Commerce for Standards and Technology and Director

ABSTRACT

Alkali-silica reaction (ASR) is a concrete degradation phenomenon in which the alkalis that are typically found in portland cement react with certain amorphous or micro-crystalline siliceous phases in the aggregate and, in the presence of moisture, form an expansive gel that is capable of cracking the concrete and generating macroscopic expansion. As the cracking occurs and progresses, there is a change in the mechanical properties of the concrete. Unfortunately, there is no standard guide or industry best practice for quantifying the reduction in the mechanical properties and the commensurate reduction in the structural capacity of ASR-affected elements. Furthermore, 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. Therefore, although there are standardized test methods to characterize the susceptibility of a specific concrete mixture to future ASR degradation, there is no standardized procedure for assuring that a concrete mixture will be entirely immune to ASR throughout its intended service life.

A scoping study of alkali-silica reaction in concrete is performed to support future activities that include evaluating the effects of ASR on the structural capacity. The study begins by summarizing the current knowledge of a number of technical topics related to the diagnosis, maintenance, and evaluation of concretes affected by ASR. The summary is then used to identify knowledge gaps for each technical topic. A technical plan is developed for filling in the knowledge gaps and for providing the tools that are needed to evaluate structural capacity of ASR-affected concrete and estimating the useful service life.

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Alkali-silica reaction (ASR) is a concrete degradation phenomenon in which the alkalis that are typically present in concreting materials react with certain amorphous or micro-crystalline siliceous phases that can be present in the aggregates and, in the presence of moisture, form an expansive gel that is capable of cracking the concrete and generating macroscopic expansion. As cracking occurs and the expansion progresses, there is a loss of the mechanical properties of the concrete, and a commensurate decrease in the structural capacity of the affected elements. Because this is a form of internal degradation, and because there may be sufficient moisture in the concrete itself for ASR to progress in the absence of external moisture, long-term solutions can be limited.

From a safety perspective, an important consideration is the remaining capacity of a structure exhibiting distress due to ASR. Determining mechanical properties from cores taken from the structure can be problematic for a number of reasons. First, the extent of the degradation will vary throughout the element as a function of the moisture content, and as a function of the degree of restraint provided by the steel reinforcement. Also, it may be difficult to predict the properties of the concrete using cores taken from the structure because the size of the defects caused by the ASR may be large compared to that of the cylinder (resulting in anomalously low tested strength), but small compared to the structure (suggesting there may be sufficient capacity). Alternatively, one could relate the relative change in concrete strength to the relative extent of the reaction. The challenge with this approach is that there is no reliable means of estimating the degree of the reaction in an existing concrete structure.

For safety-related concrete structures that require extended periods of safe operations, a monitoring strategy is needed that can predict the future evolution of the reaction to ensure that there is sufficient time to execute a safe cessation of operations. Because the evolution of mechanical properties as a function of the degree of reaction is not known, near linear extrapolations of past changes in behavior have not been validated.

A scoping study of alkali-silica reaction in concrete is used to identify knowledge gaps in the evaluation of the present capacity of concrete structures affected by ASR, and the prediction of the future loss of structural capacity. The gaps are identified through a literature search of journal articles, standards, and codes related to ASR. Based on the gaps identified, a technical plan is proposed for closing each knowledge gap.

For existing structures, the technical plan includes activities to support the evaluation of the current state of the structure and activities to support the estimation of the future performance of the structure. The plan focuses on modifying the ACI 318 relationships for estimating strength, modulus of rupture, and modulus of elasticity from the compressive strength of distressed concrete; these are critical parameters in a structural evaluation. The assumption is that these material properties decrease as a function of the degree of degradation, which is either the equivalent degree of free expansion, or the extent of the chemical reaction. The structural testing consists of making large-scale specimens with reactive aggregate and measuring the mechanical properties and the expansion of these elements over time. At the same time, samples are extracted and tested to determine the mechanical properties.

In concert with the mechanical testing, extracted specimens will be evaluated to determine the degree of the degradation. A number of tests for characterizing the degree of degradation will be considered: residual expansion tests and petrographic tests. The purpose of this testing is to identify reliable *observables* in the field that can be used in existing structures to determine the extent of the reaction, so that one may estimate the amount of future expansion to be expected. It is expected that a relationship

between core test values and the mechanical properties of a reinforced concrete element will depend, in part, on the extent of the reaction.

By using a number of different concrete mixture designs that are representative of NPP mixture designs, a relationship will be developed between the degree of the reaction and the modification needed to the ACI 318 relationships for estimating mechanical properties required to evaluate structural capacity.

The remaining technical plan addresses predicting the future extent of ASR degradation as a function of time. Of the current approaches being used to estimate future properties of ASR-affected concrete, the one recommended here is a first-order kinetic approach that captures the contribution of the primary factors affecting the rate of ASR. Although the resulting model will not have the accuracy of a more sophisticated model, it should provide general guidance for estimating the progression of the reaction with time. From this prediction, one can use the relationships developed from the mechanical testing for the ACI code parameters to predict the future mechanical properties of the concrete, and thus evaluate the future structural capacity of a structure exhibiting distress due to ASR.

ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASR	Alkali-Silica Reaction
ASTM	(formerly) American Society for Testing and Materials, (presently) ASTM International
DRI	Damage Rating Index
FHWA	Federal Highway Administration
NIRAS	Nonlinear Impact Resonance Acoustic Spectroscopy
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
NPP	Nuclear Power Plant
ORNL	Oak Ridge National Laboratory
SDT	Stiffness Damage Test

1 INTRODUCTION

Alkali-silica reaction (ASR) was identified decades ago (Stanton 1940) as a degradation mechanism in concrete whereby a reaction between the alkalis in the cement and certain siliceous phases in the aggregate produces a gel that causes an expansion that leads to cracking and strength loss (Hansen 1944, Taylor 1990). The gel forms initially in the partially saturated pore space of the hardened cement paste that binds the aggregate together. Because the resulting gel is hydroscopic, which is how the pressure is generated, water is a key component to the reaction and subsequent damage by cracking. Generally, the reaction rate is relatively slow, so the onset of cracking can occur years or decades after construction, depending on the reactivity of the mineral phases and the alkalinity of the pore solution.

The conceptual model for ASR and the consequent damage is shown schematically in Figure 1, which is taken from Deschenes et al. (2009). Inside the concrete are reactive aggregates containing siliceous or microcrystalline silica phases. The hydroxyl (OH^-) and alkali species (e.g., K^+ and Na^+) are in solution and react with the siliceous phases to form an expansive hydroscopic gel. As the gel absorbs water, it expands, generating stresses that can be in excess of 10 MPa (nominally 1500 psi) (Rigden et al. 1995, Ferraris et al. 1997). These stresses are sufficient to generate cracking, both in the aggregate and in the surrounding hardened cement paste, and can even cause macroscopic expansion of the structure.

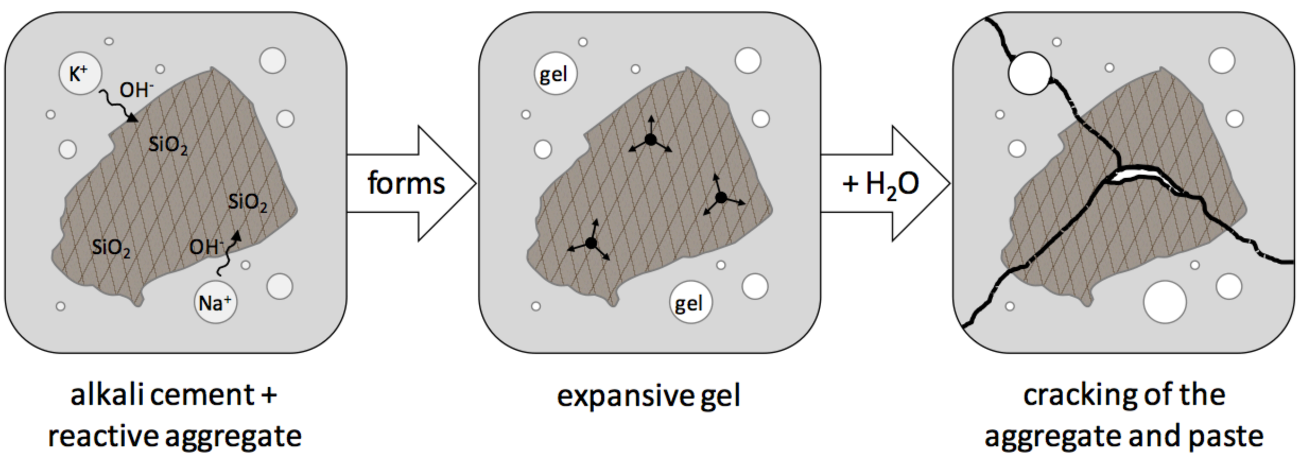

Figure 1. Schematic representation of alkali-silica reaction and cracking in concrete (from Deschenes et al. 2009). The process is shown in three stages: hydroxyl and alkali species react with the silica to form a gel; the gel absorbs water, creating expansive forces; and the stresses can ultimately generate sufficient stress to crack both the aggregates and the surrounding paste.

At the microscopic length scale, the reaction occurs in two stages. The initial stage is dissolution of silica on the surface of the reactive phase within the aggregate. At the interface between the reactive phase and the alkaline pore solution, the hydroxyl ions (OH^-) attack the silanol groups (Si-OH) and the siloxane bonds (Si-O-Si) of the reactive silica network. The siloxane bonds are broken and replaced with silanol bonds, which together with other silanol bonds in the reactive mineral, further react with hydroxyls (Dent Glasser and Kataoka 1981) producing $SiOH^-$:

$$\mathrm{Si-O-Si+OH^- \rightarrow Si-OH+OH-Si} \tag{1}$$

$$\mathrm{Si-OH+OH^- \rightarrow SiO^- + H_2O} \tag{2}$$

Within the alkaline pore solution, the concentration of the hydroxyl (OH^-) species is nearly equal to the combined concentration of the potassium (K^+) and sodium (Na^+) species. The reaction mechanisms occurring in Eq. 2 are complex, and supply the pore solution with silica species that diffuse through the pore system and react with OH^-, Na^+ and K^+ to form a gel: this is referred to as the "through-solution" mechanism of gel production (Dron and Brivot 1992, 1993). The gel incorporates water, either through absorption (Dent Glasser and Kataoka 1981) or through osmotic pressure (Diamond et al. 1981). This is a somewhat condensed representation of ASR, and a broader review of the ASR mechanism can be found in Helmuth et al. (1993). Although an understanding of the alkali-silica reaction helps to inform test method development, a thorough review of the fundamental studies of the reaction is not presented here because answering any remaining fundamental questions about the reaction does not directly support a timely solution to the principal objective of this scoping study.

One of the remaining relevant technical challenges, however, is predicting the reaction kinetics from information that can be obtained from an existing structure: e.g., the aggregate mineralogy, the pore solution composition, the temperature and moisture conditions, and the structure geometry and location. Part of the challenge is identifying and quantifying the rate-controlling processes. These may include the diffusion of pore solution through the aggregate and the dissolution rate at the reactive mineral phase surface. Depending on the mineral composition and the morphology of the aggregate, and the exposure conditions, ASR may not become evident until decades after construction.

One of the practical challenges in preventing ASR in new structures is the diminishing supply of aggregates that have a history of good performance. Regionally, there may be little, or no aggregate locally available that is known to be immune to ASR. For large construction projects that require on the order of 10^5 cubic meters of concrete, it may be impractical to ship in reliable aggregate from a long distance away.

The other important challenge in mitigating ASR is the uncertainty of if or when ASR damage will occur. For many concrete structures, a 20-year service life may be sufficient to meet the required performance until the structure becomes functionally obsolete. For certain critical components of the nation's infrastructure (e.g., dams, bridges, and nuclear power plants), assurances of long-term performance can be a financial and a safety concern. Premature replacement due to failure is costly to society, and if the structural capacity is lost at a rate that is faster than anticipated, there is a potential safety risk to the public. Moreover, these larger critical infrastructural elements are not conducive to large-scale testing to assure the overall structural capacity.

1.1 Scoping Study

The breadth of ASR research and field investigations spans a wide literature base: (1) laboratory studies of the reaction and the reaction products that are published in the technical literature; (2) standardized test methods for evaluating materials; (3) codes and industry best practice guides for material selection and concrete formulation; and (4) reports on the diagnosis and condition assessment of structures exhibiting distress due to ASR.

Although the majority of these documents may not have been developed with the purpose of facilitating structural evaluation, they may nonetheless play an important role. Given the uncertainties in evaluating and predicting the capacity of a structure exhibiting distress due to ASR, a scoping study is needed to identify past work on the subject and to devise a plan for developing the engineering tools needed to support the evaluation of an existing structure exhibiting distress due to ASR. The components of the scoping study are outlined below.

1.2 State-of-the-Art Review

A state-of-the-art literature review is performed to assimilate all this knowledge in one place. Furthermore, the scope of this review is limited to assessing the capacity of a structural concrete element exhibiting stress due to ASR, and predicting the future capacity of the same element. This scope is further broken down into the specific technical needs that, when combined together, meet the overall objective. The literature search is summarized for each of these specific technical needs.

1.3 Gap Analysis

A gap analysis is performed for each of the specific technical needs by assessing the degree to which the existing body of knowledge meets the need. Because the majority of a body of knowledge was not developed to meet the critical needs covered in this report, identifying the gaps requires one to first distill the knowledge into a coherent and comprehensive whole.

1.4 Technical Plans

Technical plans are developed to meet the gaps identified for each specific technical need. The overall objective of the technical plan is to have a process by which one can assess the capacity of a structural concrete element affected by ASR, and make an assessment of the future structural performance of that element.

2 STATE-OF-THE-ART REVIEW

A state-of-the-art review was conducted to address a number of engineering issues related to the evaluation of structural concrete elements exhibiting distress due to ASR. These issues are related, broadly, to understanding the current state of the structure and forecasting future performance. There are guides that provide strategies for confirming the presence of ASR, for mitigating the effects of ASR in new construction, and for providing repair strategies for existing structures. For the problem of quantifying the extent, rate, and future potential of the ASR reaction, however, the literature was taken largely from the research community, including archival journals and technical reports.

There are many general guides that a practicing engineer can use to find understanding and guidance in mitigating and addressing ASR. The British Cement Association (1992) has published guidelines for diagnosing the existence of ASR. Hobbs (1986) and Fournier and Bérubé (2000) provide practical strategies for mitigating the effects of ASR in new and existing structures. Farny and Kerkhoff (2007) provide broad guidance in identifying, controlling, and preventing ASR, primarily through materials testing and selection. The Federal Highway Administration published a comprehensive report on the diagnosis, prognosis, and mitigation of ASR affected concrete (Fournier et al. 2010), and a surveying and tracking guide (Thomas et al. 2012b). The Institution of Structural Engineers (UK) has produced a guide for the appraisal of existing structures (ISE 1992). RILEM is developing guidance on the appraisal and management of structures exhibiting damage due to expansive aggregate (Godart et al. 2012, Godart et al. 2013). Although each of these guides serves a purpose, none provides guidance for evaluating the structural capacity of a structure exhibiting distress due to ASR.

2.1 State, Severity, and Rate of ASR

There are a number of reliable techniques for confirming the presence of ASR in existing structures, most notably petrographic analysis and staining tests. These tests can be an indirect indication of the severity of ASR by defining the spatial extent of the affected concrete. Unfortunately, these tests only indicate the presence of ASR on a surface that is accessible; the presence of ASR at greater depths can only be inferred unless cores are removed. Regardless, it is not possible to relate test results to the state/extent of the reaction (i.e., initial stages vs. later stages), or the past and current rates of the reaction.

Visual Inspection: The most common way of characterizing the state of (advanced) ASR reaction is through visual examination. Distress due to ASR can manifest itself in a number of indicators: unidirectional cracks, map (random pattern) cracking, closed joints, spalled concrete surfaces, and relative displacement of different portions of a structure (Farny and Kerkhoff 2007). Stark (1991) collected examples of ASR cracking in highway structures, along with descriptions for distinguishing among cracks due to different degradation mechanisms. A recent field identification handbook published by the FHWA (Thomas et al. 2012a) provides a description and some examples of a number of visual symptoms: cracking, expansion, localized crushing of concrete, extrusion of joint material, surface pop-outs, and surface discoloration.

Surface Staining Methods: Over time, the gel resulting from ASR is forced through the pores, and if sufficient pressure is generated in the hydrated cement paste, cracks will form that (may) eventually propagate to the surface. The gel will flow through these cracks and eventually show at the surface as a white, yellowish, or colorless fluid that appears waxy, rubbery, or hard (Farny and Krikhoff 2007). Two surface chemical tests exist for identifying the presence of ASR reaction gel (Powers 1999). Natesaiyer and Hover (1988) developed a surface test in which uranyl-acetate is applied to the surface, rinsed with water, and the surface is viewed under ultraviolet light; this test is described in the Annex to ASTM C856. Guthrie and Carey (1998) developed a similar method in which sodium cobaltinitrite is applied to the surface, which reacts with the potassium in the ASR gel and results in a yellow stain. A second solution, rhodamine B, is applied to the surface, and if ASR gel is present, it produces a pink background and a darker pink stain where reaction gel is present. Neither staining test, however, can give an indication as to the severity or rate of the ASR reaction.

Petrographic Examination: Petrographic test methods (ASTM C295/C295M, ASTM C856 or AASHTO T 299) have been proven to be effective in identifying many reactive minerals in aggregates or reaction products in concrete (Hurcomb 2009). A prepared concrete specimen is examined with optical (Walker et al. 2006) and scanning electron microscopes (Clark et al. 1992). Under optical analysis of a cross section, the silica gel appears as a darkened area in the aggregate, or around its edges (Farny and Kerkhoff 2007). FHWA recommends conducting a petrographic examination of the aggregate to be used in new construction in accordance with ASTM C295/C295M (Thomas et al. 2008). Rivard et al. (2002), Rivard and Ballivy (2005), and Grattan-Bellew and Mitchell (2006) have assessed the effectiveness of the Damage Rating Index (DRI) that is based on a number of petrographic features observed on a thin section: e.g., cracked aggregate, cracked paste, or air voids lined with gel. Each observable is given a rating factor, and the overall rating was a sum of the individual factors. Although the method yields results that are correlated to the extent of expansion, the method yields comparative results, and the DRI cannot be used to make an absolute statement about the extent or the rate of the reaction without a pre-existing correlation. From a practical perspective, Thomas et al. (2012b) presented applications of the use of DRI to bridge structures for the diagnosis of ASR.

Quantification of Cracking: The Cracking Index (CI) is a type of crack mapping analysis that attempts to quantify the degree of cracking as an indication of the severity of the reaction. The CI method was introduced by the Laboratoire Central des Ponts et Chaussées in 1997 (LCPC 1997) (Fournier et al. (2010) provide an description in English) as a tool for assessing transportation structures affected by ASR. The method consists of drawing a square (approximately 0.5 m on a side), on the surface of the affected concrete and recording the total width of cracks at the intersection of the cracks and the sides of the square. The numerical result is the ratio of the total width (millimeters) of the intersected cracks to the total length (meters) of the sides of the square; the result is expressed in units of (mm/m). Optionally, one can report the “horizontal” and “vertical” components of the CI separately. Fournier et al. (2010) provide criteria for determining whether more detailed investigations are needed: a CI greater than 0.5 mm/m, and/or individual crack widths greater than 0.15 mm.

Ben Haha et al. (2007) developed an image analysis technique, applied to polished cross sections, to quantify the degree of reaction and correlated this to the amount of expansion. Dunant and Scrivener (2010) extended this model to include a prediction of the loss of stiffness as a function of the extent of the reaction.

Properties of Silica Gel: Detecting ASR gel from bulk analysis is difficult because the chemical composition of the gel is similar to the calcium-silica-hydrate gel that forms from the reaction of water and portland cement. Therefore, new techniques for detecting ASR gel in concrete will need to exploit properties of the gel that make it distinguishable from the other phases present. Studies have been conducted to quantify the properties of the amorphous silica gel emanating from the reaction site. Hamoudi et al. (2008) combined X-ray diffraction, nuclear magnetic resonance spectroscopy, and infra-red Fourier transform spectroscopy to characterize the gel formed from high purity silica reacting in an alkaline environment at elevated temperatures. Cong et al. (1993) used nuclear magnetic resonance spectroscopy to study polymerization of natural materials, reacted with potassium hydroxide in the presence of calcium hydroxide, and noted that the reaction products were similar to the calcium silicate hydrate gel produced by portland cement hydration. Presently, however, no single technique has emerged that can provide a reliable quantification of the ASR gel.

Stiffness Damage Test: The Stiffness Damage Test (SDT) was proposed by Chrisp et al. (1993) to characterize the extent of damage in ASR-affected concrete, and it has been adopted in the United Kingdom by the Institution of Structural Engineers (ISE 1992). The method uses cyclic (5 cycles) uniaxial compressive loading, typically between 0 MPa and 5.5 MPa (800 psi), of concrete core samples, to quantify changes in certain mechanical properties:

1. The reduction in the Young's modulus of elasticity, and
2. The energy dissipated during the load-unload cycles, which corresponds to the area of the hysteresis loops in a stress-strain plot, and
3. The accumulated plastic strain after these cycles, which is related to the closure of the existing cracks and to a slip mechanism, and thus represent a measure of the damage in the specimen (microcracking) in the direction of the applied stress.

One of the drawbacks to this method is that correlations are needed to relate the results of the SDT method to the expansion measured from the concrete prism tests (ASTM C 1293) discussed in Section 2.7. This is a serious drawback for an existing structure, particularly one that is decades old and for which there are no samples of the original aggregate. In this case, the process would have to be modified, possibly by using the aggregate extracted from the affected structure; this approach would only provide an approximate measure of the subsequent expansion.

Smaoui et al. (Smaoui et al. 2004a, Smaoui et al. 2004b, Bérubé et al. 2005) performed an extensive study to compare the effectiveness of the surface cracking index (CI), the stiffness damage test (SDT) (but cycling up to 10 MPa), and the damage rating index (DRI) in estimating the extent of ASR reaction. In the third report (Bérubé et al. 2005), the methods were compared when applied to existing structures. The authors found that surface crack widths provided good estimates of concrete expansion if the degradation was sufficiently severe. The DRI method was not able to differentiate some of the most affected concretes from the lesser affected ones. The SDT method proved to be the most promising method for estimating non-prestressed concrete expansion; the method underestimated expansion in prestressed concrete members. More recently, Sanchez et al. (2012) have shown that the best results for determining the internal condition of concrete affected by ASR can be obtained when the concrete specimens are loaded to about 40 % of their design strength.

Ultrasonic Assessment of ASR Reaction: A number of techniques have been proposed that use ultrasonic stress waves to assess the severity and rate of ASR. Saint-Pierre et al. (2007) used Fourier analysis of the compressive wave pulse through a cylinder specimen to relate the pulse velocity and the wave attenuation at 100 kHz to the expansion. With the growing number of acoustic techniques for detecting cracking in concrete, Kodjo et al. (2011) have investigated ultrasonic techniques that may be able to distinguish between cracking due to ASR and cracking from mechanical damage. However, the test requires analyzing the creep response of specimens, and although comparative differentiation was possible, it is not clear whether an absolute determination can be made. Recently, nonlinear resonance spectroscopy techniques have shown promise in detecting defects in concretes having distributed thermal damage (Payan et al. 2007), and the same technique may be applicable to ASR damage. The concept was extended to a nonlinear impact resonance acoustic spectroscopy (NIRAS) principle for detecting ASR damage in concrete (Leśnicki et al. 2011), whereby changes in the nonlinear acoustic response of a prism specimen undergoing ASTM C 1293 testing are compared to the expansion occurring during the test. The results suggest that the test might be used to evaluate the evolution of the ASR reaction, and it can be applied to cores taken in the field, suggesting the possibility of a future field test.

2.2 *In-situ* Mechanical Properties of ASR-Affected Concrete

During the past several decades, a number of studies aimed at assessing the effects of ASR on the mechanical properties of concrete have been carried out (Ahmed et al. 1999, 2002 and 2003, Bollinghaus 1985, Chana 1988 and 1989, Chana and Koroboski 1991 and 1992, Clark 1989, McLeish 1990, Deschenes et al. 2009, Nixon and Hobbs 1988, Smaoui et al. 2006, Swamy and Al-Asali 1988). These studies focused on determining the extent of reduction of the compressive and tensile strengths and the modulus of elasticity of ASR-affected concrete. In general, the compressive strength was determined by testing cores (taken from either *in-situ* structural members or laboratory specimens), standard test cylinders (laboratory conditioned for accelerated expansion), or cubes (prepared from cores or laboratory conditioned cube specimens for accelerated expansion). The tensile strength, in all cases, was determined by splitting tensile tests of cores or standard cylinders or, to a lesser extent, direct tension tests of cores. The modulus of elasticity was determined either from axial compression or direct tension tests or simple beam tests.

Provided water is available in the pore system, the compressive strength of non-ASR-reactive concrete increases as it ages due to additional hydration. On the other hand, the above-mentioned studies have shown that the compressive strength of ASR-affected concrete undergoes a progressive reduction in strength with increasing expansion (Chana 1988, Nixon and Hobbs 1988, and Swamy and Al-Asali 1988). These studies presented the degradation of strength of concrete as a function of the expansion. For example, the reduction in strength reaches about 29 % at 0.39 % expansion, as reported by Smaoui et al. (2006).

The tensile strength of *in-situ* concrete determined by testing of cores (either splitting tensile test or direct tension test) would vary substantially depending on the location of the cores with respect to the placement (upper half or lower half of a beam, for example) and the direction of loading with respect to the general direction of microcracks. It was noted by Smaoui et al. (2006), that the direct tensile strength is particularly sensitive to the cracks perpendicular to the direction of the applied load. In addition, because the development of microcracks due to ASR in a structural member is heterogeneous, it is reasonable to expect that the variation of the tensile strength of ASR affected concrete from core tests would be large. Both McLeish (1990) and Deschenes et al. (2009) have shown a large variation of tensile strength using cores. Therefore, it is reasonable to expect that the reduction of the *in-situ* tensile strength of ASR-affected concrete members would vary substantially depending on (1) the location where cores are taken, (2) the test method (splitting tensile test vs. direct tension test), and (3) the direction of applied tensile stress with respect to the general direction of cracks due to the ASR expansion.

The modulus of elasticity can be determined from the stress-strain relationship obtained from the compression and direct tension tests. Both tests yield about the same elastic modulus value (Smaoui et al. 2006). In the case of nonreactive concrete, the stress-strain relationship remains relatively constant with time. However, because the stress-strain relationship of ASR-affected concrete changes over time, the modulus of elasticity also changes. The reduction in the modulus can be significant (up to 30 %) even at only 0.04 % expansion (Samoui et al. 2006). The reduction the elastic modulus increases as the concrete expands further due to ASR.

The transfer of stress between reinforcement and concrete is a complex mechanism that is influenced by a number of factors. Bond or anchorage capacity between the reinforcement and the concrete is necessary to ensure composite action of the two materials in resisting applied load. In general, the anchorage capacity of a reinforcing bar in concrete, depends on the type of reinforcement, the depth of concrete cover and the tensile strength of the cover concrete. Depending on the type of reinforcing bar, anchorage capacity is developed by (a) chemical adhesion between the steel and the concrete, (b) frictional resistance to sliding after the adhesion has been broken and (c) bearing of the concrete against the reinforcing bar surface deformations (or lugs). Research has shown that bond strength is proportional to the tensile strength of concrete (Ferguson 1966, Van de Meer 1975, Orangun et al. 1977). Limited research on the effect of ASR on the bond strength (Ahmed et al. 1999, Chana 1989) shows that ASR causes substantial reductions in the anchorage capacity, as compared with that of the sound concrete. Conventional pull-out tests also have shown (Hobbs et al. 1987) that as much as a 50 % reduction in the pull-out strength was observed in ASR-affected concrete if there was no transverse reinforcement to confine the concrete.

2.3 *In-situ* Strength of ASR-Affected Concrete

To assess the adequacy of the structure, the actual *in-situ* concrete strength must be known. At present, the transient properties of ASR-affected concrete are estimated by testing of cores taken from the actual structural members. Because ASR activity is not uniform throughout the member cross section, the concrete strength determined from cores can vary through the cross section. Consequently, the strength in the central and cover regions of a concrete member could vary significantly. In addition, the variability of concrete strength through the cross section is affected by the location within a placement of concrete and the direction of testing. This variation increases as a result of ASR expansion and is non-uniform (Chana and Koroboski 1991) because: (a) the structural member would be subjected to differing restraints due to loading, geometry and reinforcement, and (b) the extent of expansion and cracking can vary in different directions. As a result, the strength derived from tests of cores taken from an ASR-affected concrete structure may vary considerably. It should be pointed out that the non-uniformity also exists in sound concrete members. However, the range of the non-uniformity is known and reasonably well documented. Furthermore, the presence of transverse reinforcement can also influence actual *in-situ* strength of the ASR-affected concrete (Chana and Koroboski 1991). All these factors must be considered in determining the strength of the *in-situ* concrete. This will require testing more cores for ASR-affected concrete than are typically tested for sound concrete.

In addition, the long-term relationship between compressive strength and tensile strength of *in-situ* concrete must be established because design is based on the code-provided relationships, which are based on sound concrete. As a result, the failure mode may change from that of the original design assumptions. Thus, the performance of structural members may change over their service life due to ASR degradation of concrete.

2.4 Applicability of ACI Documents to ASR-Affected Concrete

ACI standards related to design and construction of nuclear power plants, ACI 349 (Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary), and ACI 359 (Code for Concrete Containments) are for sound concrete. These standards assume that the materials are selected so that ASR is prevented. Similarly, ACI 318 (Building Code Requirements for Structural Concrete and

Commentary), to which both ACI 349 and ACI 359 refer, is for sound concrete. Thus, ACI 318, ACI 349 and ACI 359 do not include any provisions for assessing the strength of ASR-affected concrete members.

There are several ACI documents (committee reports) that are relevant to ASR. These are:

a. ACI 349.3R (Evaluation of Existing Nuclear Safety-Related Concrete Structures)
   This document provides information on inspection of concrete nuclear structures subjected to age-related degradation including chemical attacks, thermal exposure, cement aggregate reactions (ASR) and others. It also suggests test methods that could be used to evaluate potential for ASR.

b. ACI 224R (Control of Cracking in Concrete Structures)
   This document provides information on the principal causes of cracking and recommends crack-control procedures.

c. ACI 221.1R (Report on Alkali-Aggregate Reactivity)
   This document summarizes currently available information on alkali-aggregate reactivity including alkali-silica reactivity (ASR) and alkali-carbonate reactivity (ACR). It provides information on design of concrete mixture (materials) and test methods to evaluate potential for ASR. The document also provides limited information on repair methods for cracks.

2.5 Managing the Effects of ASR

The hydroelectric dam community has been studying management strategies for ASR-affected structures for many years. Fournier et al. (2004) discussed options for determining the structural integrity and evaluating the potential for future deterioration, and provided a process for taking appropriate management actions. Fournier et al. (2010) and Charlwood et al. (2012) discuss managing the long-term expansion, and options for maintaining serviceability.

In any structure, the ongoing chemical reaction can be difficult to stop using repair or rehabilitation. The three key contributors to ASR are reactive aggregate, alkalinity, and water, and one can slow the rate of reaction by eliminating one or more of these contributors. The most common approach is to reduce access to water, typically by making the structure impermeable to water. This approach works best for stand-alone elements like columns. For a buried structure, the concrete-soil interface may be inaccessible. Furthermore, for a buried structure like a tunnel in contact with groundwater at the exterior surface, drying only the interior of the structure will have the effect of driving more water through the structure, and the evaporation front near the interior surface will concentrate alkalis, thus possibly accelerating the ASR near the interior surface. Flushing an element with excessive water to dilute the alkalis is problematic because it will difficult to ensure that the water will infiltrate the entire member; this would likely only be attempted if the structure exhibited extensive cracking, but the water would almost certainly only flow through the cracks and not through the affected hardened paste. Furthermore, the net effect may be to provide a reservoir of water for continued reaction in the uncracked portions of the concrete. As a result, there are no established methods or procedures at present to prevent progress of deterioration after the initiation state of the ASR.

On approach that may have promise in reducing future ASR-induced expansion is the use of sealers to prevent additional moisture ingress. Bérubé et al studied the effectiveness of different sealer technologies on laboratory specimens (Bérubé et al. 2002a) and highway median barriers (Bérubé et al. 2002b). Some of the technologies were effective in reducing expansion to an acceptable level, if applied early on in the ASR reaction, and that subsequent expansion was strongly correlated with the change in concrete mass due to moisture transport. Drimalas et al. (2012) also reported on the effectiveness of sealers on highway structures. They concluded that topical silane treatments can be effective in slowing down expansion, but developing conclusive evidence may require many years.

Another solution to managing the effects of concrete degradation is to catalog the performance of existing structures. The Oak Ridge National Laboratory (ORNL) has created a Nuclear Concrete Materials Database (Naus 2011, Ren 2012) using an existing ORNL materials database infrastructure. Some of the ultimate uses of the database would be to facilitate electronic and mathematical processing for analysis and modeling in support of facilities management. In addition, the FHWA has developed a guide for surveying and tracking alkali-silica reactivity in concrete (Thomas et al. 2012b). The guide was intended to help State Highway agencies survey and track transportation infrastructure that has been affected by ASR, primarily resulting in cracking and expansion.

2.6 Numerical Modeling of ASR

A model for the pore pressure has been developed as a function of aggregate size and paste transport properties (Bažant and Steffens 2000). The model was based on a spherical reactive glass particle that generates gel uniformly over its surface, and the predicted pressure generation was consistent with the observed pessimum aggregate size effect observed by Meyer and Baxter (1998) and Jin (1998). Further modeling is needed, however, to account for the role of aggregates in the early stages of reaction and the role of the hardened paste in the later stages of the reaction (Dunant and Scrivener 2012).

Ulm et al. (2000) developed a thermo-chemo-mechanical model for ASR in concrete. Although the model yields realistic responses, it requires a large number of material parameters as inputs, and it is not clear to what extent that model is applicable to existing structures already exhibiting ASR damage. (One might use such a model as part of a monitoring program where future observations are used to improve the model parameters). Saouma and collaborators (Saouma and Perotti 2006, Saouma et al. 2007) have developed structural models using the functional form of the thermodynamic model to predict future properties; the thermodynamic model parameters are determined empirically from measured mechanical properties of the concrete.

Bangert et al. (2004) developed a chemo-hygro-mechanical model for ASR that incorporates the silica dissolution reaction, a mixture model for the volume change, a kinetics model, the viscosity of the gel, and the saturation dependent permeability. The model predicts the expansion, the expansion rate, the damage parameter (ratio of damaged cross section to the original cross section), and the reaction force as a function of the load factor. Although it is an interesting comprehensive model, the authors do not discuss the applicability of the model to structural concrete elements containing steel reinforcement. Pesavento et al. (2012) developed another model that accounts for non-isothermal and changing moisture conditions. Although this model is able to reproduce strain and mass variations measured in the laboratory, there are many model parameters. Recently, Puatatsananon and Saouma (2013) have developed a chemo-mechanical model for ASR that also incorporates the effects of internal moisture and ion concentration on the transport properties of the concrete. It is a two-stage model that couples a finite difference transport (pore solution ions and ASR gel) model to a finite element nonlinear analysis to estimate the resulting expansion.

2.7 ASR Prevention for New Construction

Mixture Proportioning Guides: Industry organizations provide guidance in developing concrete mixtures to mitigate the potential effects of ASR if aggregates that exhibit some measureable reactivity have to be used. The Portland Cement Association provides guidance for the specification of concrete (PCA 2007). The recommendations typically limit the total alkali to less than 0.5 % on a mass basis for ordinary portland cement mixtures, and increase the allowable alkali contents with increasing replacement of portland cement with pozzolans, or slag cement, or both (Lane and Ozyildirim 1995, Lane and Ozyildirim 1999, Thomas et al. 2008). AASHTO has adopted the Federal Highway Administration (FHWA) guides (Folliard et al. 2006, Thomas et al. 2008) for selection of concrete materials for preventing ASR, and has recently established a standard practice (AASHTO PP65) for determining the reactivity of aggregates and selecting appropriate for preventing deleterious expansion (Thomas et al. 2012c, Thomas et al. 2012d). There are also recommendations for using Class N fly ashes to mitigate ASR (Ballard et al. 2008). Alternatively, one might accept that ASR is going to happen and use fibers to resist the expansion (Bektas et al. 2006), or starve the reaction by adding additional reactive aggregate as a powder (Carles-Gibergues et al. 2008). The use of air entrainment in concrete was reported to reduce expansion due to ASR (McCoy and Caldwell 1951; Jensen et al. 1984; Pleau et al. 1989), but generally not enough to adequately prevent deleterious expansion and cracking due to ASR. Mather (1999) recommended using satisfactory slag cement or pozzolan, and maintaining the concrete's internal relative humidity below 80 % throughout its service life.

Materials Chemical Test Methods: There are test methods to evaluate both the aggregate and the cementitious materials to be used for a specific concrete (Thomas et al. 2006) that report the unrestrained expansion of a test specimen as a function of time:

- ASTM C227 (Mortar Bar Test) was the original mortar bar test. Leaching of alkalis from the mortar bars during the test, however, makes the test method unsuitable for determining critical alkali levels, and the test is not considered to provide an accurate assessment of the potential reactivity of an aggregate with a given cement.
- ASTM C441/C441M (Pyrex Mortar Bar Test) is similar to ASTM C227, but uses Pyrex (borosilicate) glass to test the effectiveness of pozzolans in mitigating ASR when used with a high alkali portland cement.
- ASTM C1260 (Accelerated Mortar Bar Method) is an accelerated mortar bar test in which the proposed aggregate is crushed and sieved, added to a prescribed mortar mixture that includes additional alkali, formed into a mortar bar (25 mm x 25 mm x 250 mm) and submerged in a NaOH solution at a temperature of 80 °C. The test requires 16 days to complete.
- ASTM C1293 (Concrete Prism Test) can be used to test either the coarse or the fine aggregate, or the combination of an aggregate with a pozzolan or slag. The specimen is made with both coarse and fine aggregate, includes the addition of an sodium hydroxide (NaOH) solution to achieve a prescribed alkalinity, and the material is cast into a prism that is approximately 75 mm x 75 mm x 275 mm. The test requires a year to complete.
- ASTM C1567 (Accelerated Mortar-Bar Method) is a rapid evaluation of the effectiveness of a proposed supplementary cementitious material (SCM) to mitigate the effects of ASR for a given fine or coarse aggregate. Test conditions are the same as in ASTM C1260, and the test requires 16 d to complete.

- Autoclave Mortar Bar Tests (Tang et al. 1983, Fournier et al. 1991) accelerate the testing by using high temperature (150 °C) and pressure, typically on for a few days. The samples are often prepared with an alkaline mix solution and are steam cured, which accelerates the overall testing plan. These methods, however, have not yet been standardized.

FHWA has developed a guide for evaluating the reactivity of the aggregate (Thomas et al. 2008). The format is a flow chart, as shown in Figure 2, and the process involves two of the test methods described above. The resulting decisions are either that the aggregate is non-reactive and no precautionary measures are needed, or the aggregate is alkali-silica reactive and either preventive measures are needed or the aggregate should not be used.

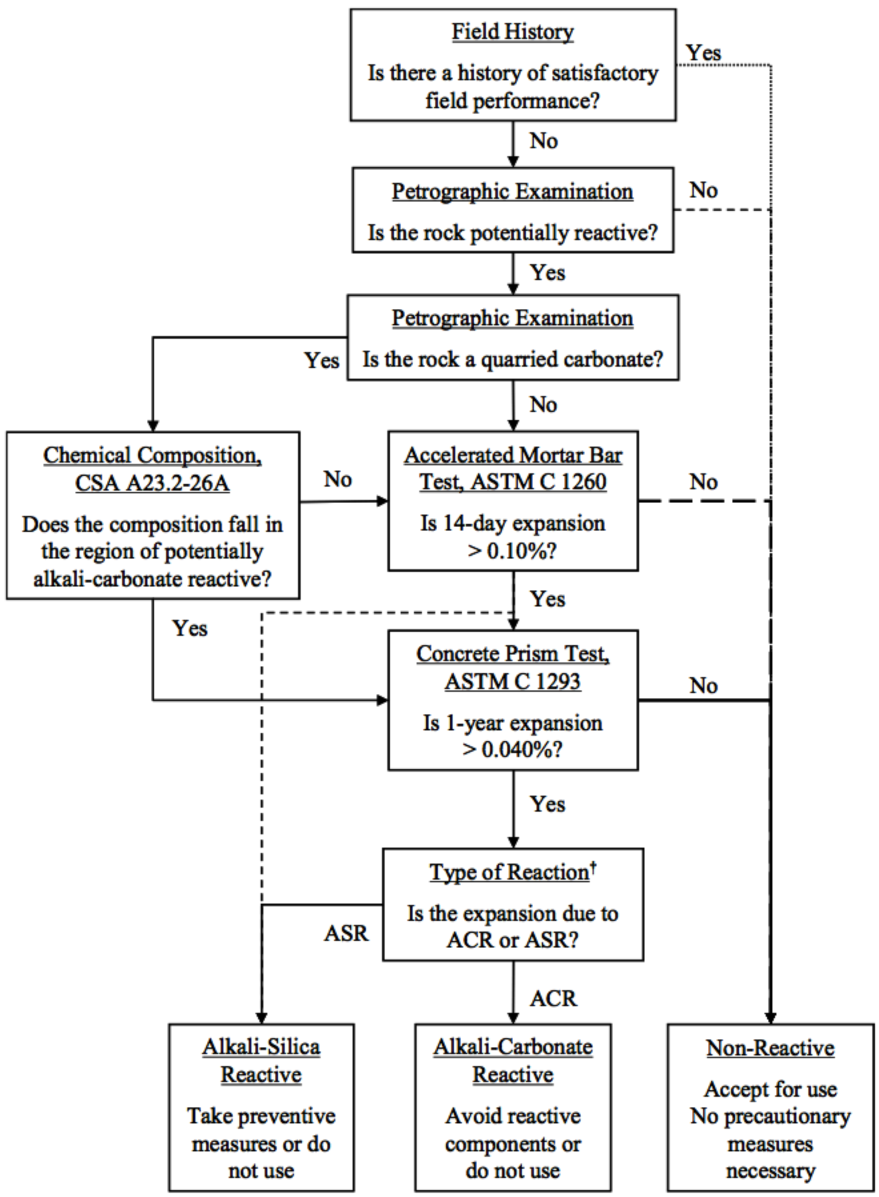

Figure 2. Sequence of laboratory tests for evaluating aggregate reactivity (from Thomas et al. 2008)

2.8 Effect of ASR on Transport Properties

There are a number of non-ASR distresses that may be exacerbated by the effects of cracking due to ASR (Thomas et al. 2012a). Even if the structural performance is acceptable, the cracks can act as "superhighways" for the ingress of dissolved species. For example, a steel reinforced concrete element in contact with a chloride containing groundwater can be susceptible to corrosion of the steel reinforcement, which would eventually degrade the structural performance of the element.

There are a number of standardized test methods for characterizing the transport properties (e.g., diffusivity and permeability) of concrete. Bulk diffusion can be estimated from ASTM C1556, and the electrical conductivity can be estimated from test method ASTM C1760. These tests, and the many like them, were developed for characterizing a property of sound concrete. As such, they are useful test methods for estimating the time to the onset of steel reinforcement corrosion, in the absence of cracks.

Transport through a material can be characterized by a quantity referred to as the formation factor (Snyder 2001). The formation factor is a numerical value that gives the relative *decrease* in transport through a porous materials, compared with transport through water. For example, if the diffusion coefficient of chlorides through a concrete is 100 times slower than that of chlorides through water, the formation factor of the concrete is 100. Typical formation factor values for concrete are 100 to 1000. Regardless of the condition of a concrete, transport occurs (mostly) through the water-filled space, either within the cement paste microstructure or within cracks. The formation factor accounts for the porosity and tortuosity of the microstructure (Snyder 2001), characterizing, in effect, the degree to which the path of water is *not* a straight line through a specimen.

Therefore, cracks do not change the nature of the transport. Instead, cracks (almost always) change the formation factor. As expected, water-filled cracks can become "superhighways" for transport, given that transport through these "wide straight paths" is 100 to 1000 times faster than through the cement paste microstructure. Although the overall formation factor for a concrete is a weighted average of the corresponding values in the cement paste and the cracks, cracks parallel to the direction of transport can overwhelm the average. A more thorough discussion of the effects of cracks on permeability is given by Snyder (2000), and a discussion of the effects of cracks on corrosion is given by Naus (2007). There is also a counter argument that diffusion along a crack can be slower than expected (Mainguy and Ulm 2001) due to solute congestion, if there is no convective transport that might flush the solute through the crack. This effect, however, occurs over time and is a result of dissolution-precipitation chemical reactions.

For transport due to hydraulic flow under a hydrostatic pressure gradient, the total flow through a crack is a strong function of the crack width. For a liquid having viscosity μ flowing through a slab having a thickness d, the rate of flow Q (volume per unit time) through a smooth-faced crack is a function of the crack length b and crack width w, and the hydrostatic pressure difference ΔP across the crack:

$$Q = \frac{w^3\, b}{12\mu}\, \frac{\Delta P}{d}\, \xi \tag{3}$$

In practice, however, cracks are not straight and smooth, so there is less flow than anticipated. There is a flow reduction due to this roughness effect, characterized mathematically in Eqn. 3 by the parameter ξ, which has a value that varies from 0.02 to 0.5 (e.g., Edvardsen (1999) proposed a value of 0.25). Some of the variability in the value of this reduction factor may be its dependence on crack width; it has been observed that the factor decreases with the increase of slab thickness (Ramm and Biscoping 1998).

This effect of cracks on transport is limited to the crack portion of the concrete. If there are surface cracks that only penetrate a (relatively) short distance to the reinforcement, the net effect is minimal (Snyder 2000). Therefore, to gauge the effect of cracks on the bulk transport coefficient, one must characterize both the topology of the cracks and the depth of the cracks.

2.9 Summary

Significant research has been conducted in the mitigation and detection of ASR in concrete. Unfortunately, relatively little research has been applied to estimating the remaining capacity of ASR-affected structures over time by relating observable quantities in the field to the mechanical properties of the concrete. Furthermore, there is relatively little technical knowledge or existing data for establishing such relationships. This gap is discussed further in the following chapter.

3 GAP ANALYSIS

While research summarized in Chapter 2 has resulted in a better understanding of mechanisms of damage to concrete by alkali-silica reactivity, there are still knowledge gaps on how to control alkali-silica reactivity, how to predict future development of cracks, and how to predict the performance of concrete structures affected by alkali-silica reaction. In this chapter, gaps in the current state of knowledge of methods for detecting ASR activity before cracks develop, for preventing further progress of crack development, for assessing the mechanical properties of ASR-affected concrete, and for predicting the progress of deterioration due to ASR are discussed.

3.1 State and Severity of ASR; Predicting Rate of Reaction

There are no reliable direct test methods for determining the degree or the rate of the ASR in existing structures. The severity of the reaction can be otherwise inferred from the degree of expansion and cracking. Unfortunately, expansion will not be detected until it becomes macroscopic (unless displacements have been monitored precisely over time), and the amount of expansion and cracking depend on the degree and the extent of the confinement provided by the steel reinforcement. In general, more cracking implies more reaction and expansion, but there is no simple relationship between the two.

For an existing structure, for which samples of the original aggregate do not exist, there are no reliable test methods for quantifying the state or the rate of ASR. One could monitor the degree of in-place expansion or cracking, but this approach has limitations: the expansion must be monitored over a sufficiently long period to observe quantifiable displacements; the degree of cracking depends upon factors, like confinement by reinforcement, that are not related to the extent or rate of the reaction. Furthermore, although the expansion often exhibits a sigmoidal shape over time, one must have data over a sufficiently long time to ascertain conclusively the stage of the reaction. Moreover, expansion vs. time curves are most often developed for unrestrained specimens such as the mortar bars and prisms used in standardized test methods.

Bulk chemical detection and quantification of the gel is also hindered by a lack of uniqueness of the ASR gel properties. The alkalis react with the silica, which can incorporate calcium from the portlandite produced during cement hydration. As a result, the chemical properties of the ASR gel are similar to the chemical properties of the strength-producing calcium-silicate-hydrate (C-S-H) gel that forms as a hydration reaction product of portland cement and water. Furthermore, the amorphous silica in the aggregate will be difficult to differentiate from the amorphous silica in the ASR gel using X-ray diffraction. There are some laboratory studies of the gel product formed under controlled conditions (Hamoudi et al. 2008), but additional laboratory research is needed to assure that one can quantify the amount the gel uniquely and consistently in field specimens.

3.2 *In-Situ* Mechanical Properties of ASR-Affected Concrete

The main mechanical properties of concrete that need to be determined for the assessment of the structural adequacy are:

a) Compressive strength
b) Tensile strength

c) Anchorage capacity of embedded reinforcement (see Section 3.3)
d) Modulus of elasticity

For non-ASR-affected structural members, if the compressive strength of concrete (f_c) is known, other properties can be determined using experimentally established relationships from non-expansive concrete. For design of concrete members, the ACI 318 Building Code (ACI 318-11) defines the splitting tensile strength (f_{ct}), the modulus of rupture (f_r) and the modulus of elasticity (E_c) in terms of the measured compressive strength (f_c):

$$f_{ct} = 6.7 \sqrt{f_c} \qquad \text{(psi)} \qquad (4)$$

$$f_r = 7.5 \sqrt{f_c} \qquad \text{(psi)} \qquad (5)$$

$$E_c = 33\, w_c^{1.5} \sqrt{f_c} \qquad \text{(psi)} \qquad (6)$$

where w_c is the density (unit weight) of the concrete in units of lb/ft^3. The numerical coefficients (6.7, 7.5 and 33) in these equations are derived from the test results of concrete not affected by ASR. Because the degree of reduction due to ASR on the tensile strength and the modulus of elasticity is not the same as the degree of reduction on the compressive strength, the above ACI 318 equations are not applicable to ASR-affected concrete. At present, no accepted equations such as (4), (5) and (6) for the mechanical properties of ASR-affected concrete are available to estimate its tensile strength, modulus of rupture, or modulus of elasticity.

Smaoui et al. (2006), based on laboratory test results of unrestrained laboratory cylinders, have shown (Figures 3 and 4) that the relationships between the mechanical properties and the expansion of concrete due to ASR could be developed. By testing ASR-affected concrete specimens under triaxial stress conditions simulating the internal confinement pressure due to ASR, similar relationships can be developed for ASR-affected concrete that would be more representative of in-place strength. It should be pointed out that routine tests are conducted on unconfined core specimens and the resulting strengths may not be indicative of the strength under the triaxial stress conditions that exist in massive structures due to confinement of ASR expansion.

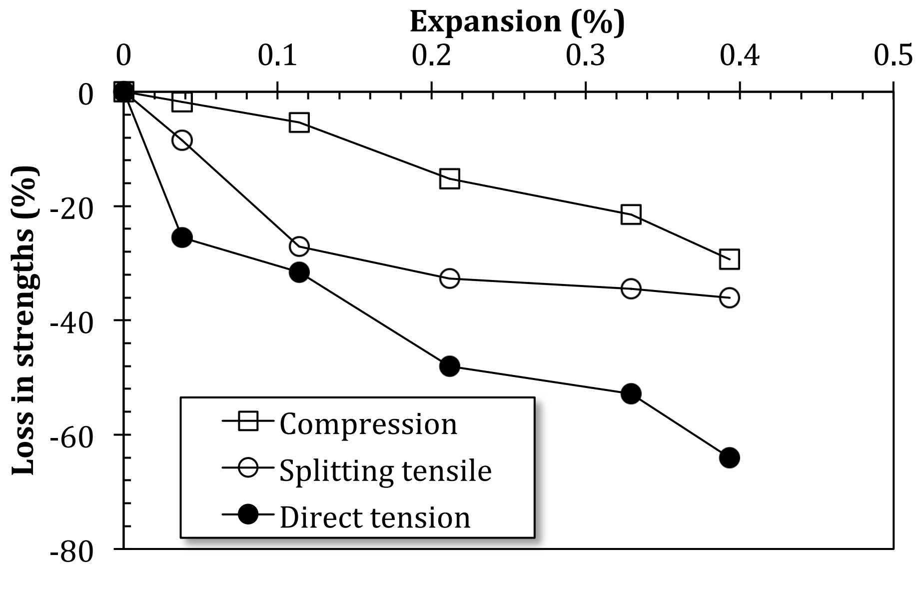

Figure 3. Relationships between ASR expansion and loss in compressive and tensile strengths (from Smaoui et al. 2006)

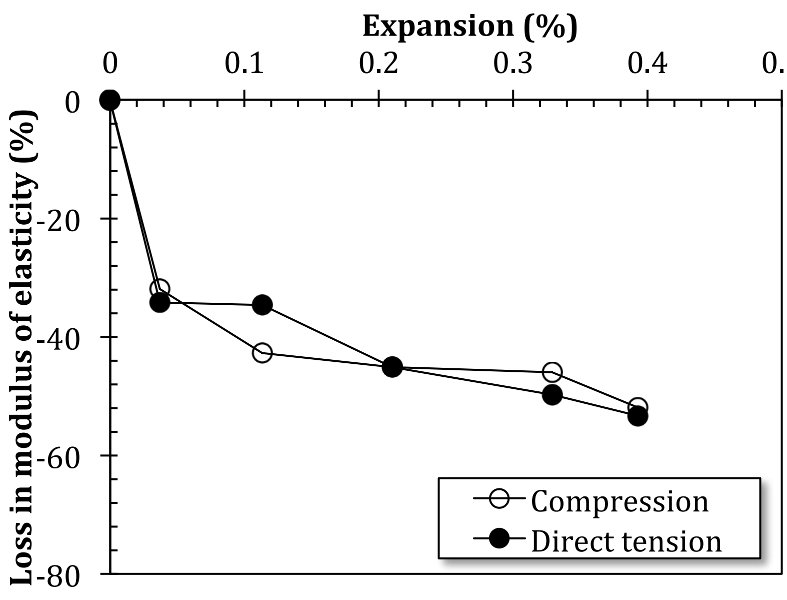

Figure 4. Relationship between ASR expansion and loss in modulus of elasticity (from Smaoui et al. 2006)

It should be pointed out that, the long-term relationship between the compressive and tensile strengths of *in-situ* concrete must be established because the original design was based on the code-provided relationships, which are based on ASR-unaffected concrete. As a result, the failure mode of the ASR-affected concrete structure may change from that of the original design assumptions. Thus, the performance of a structural member may change over its span of service life due to the ASR degradation of concrete.

3.3 Effects of ASR on Anchorage of Reinforcement

The fundamental requirement for anchorage of reinforcement is that the strength of the anchored bar must develop fully prior to being pulled out from concrete due to the tension force in the bar. In general, this requirement is met by providing adequate embedment length, hooks, mechanical anchorage devices or a combination of these. The development length approach for anchorage of deformed bars in tension is adopted in the ACI 318 Standard because the actual bond stress varies along the length of a bar anchored in concrete.

For a straight bar surrounded by a mass of concrete, the length of embedment should be adequate to develop its yield strength without being pulled out by the force applied at the free end. For standard deformed reinforcing bars embedded in non-ASR concrete, the required development length (l_d) can be expressed as a function of a number of parameters:

$$l_d = \Phi\left(f_y/f_{ct}\right) \alpha \, \beta \, \gamma \, d_b \tag{7}$$

where Φ is a numerical coefficient, f_y is the yield strength of the reinforcing bar, f_{ct} is the splitting tensile strength of concrete, α is a bar location factor, β is an epoxy coating factor, γ is a bar diameter factor, and d_b is the bar diameter. As discussed in Section 2.4, the provisions in ACI 318 and ACI 349 are for sound concrete. Thus the numerical values given in these standards cannot be used to determine Φ and f_{ct} for the ASR-affected concrete. Furthermore, if hooked bars and mechanical anchorage devices are used, additional modification factors must be determined experimentally. The development length requirement is further modified if transverse reinforcement is used.

3.4 Capacity of ASR-Affected Concrete Structures

The assessment of the capacity of ASR-affected concrete structures requires the determination of the following factors:

a) Induced stresses in concrete and reinforcement due to ASR expansion
b) Mechanical properties of ASR-affected concrete under such induced stresses

Once these factors are determined, structural capacity analysis can be performed using the total stress condition and the modified mechanical properties of concrete. The expansion of concrete due to ASR is restrained by adjacent unexpanded concrete, reinforcement, and stresses due to loads on the structure. These restraining factors should be considered in assessing the stress condition in concrete and reinforcing steel. At present, no standard procedure is available to determine the expansion of concrete due to ASR. As stated in Section 3.2 and Section 3.3, there are no recommended guidelines for relationships among the mechanical properties of ASR-affected concrete.

As indicated in Section 2.3, ASR reactivity is not uniform throughout the cross section of a concrete member. Thus, the concrete strength determined from cores can vary across the cross section. In order to determine the mechanical properties of the weakest parts of the structure, it would be desirable to detect, using a non-intrusive method (such as nondestructive test methods), the locations where ASR is most active. At present, no standardized nondestructive testing methodologies are available to map ASR activity in structural members.

3.5 Managing the Effects of ASR

There is no definitive means of managing the effects of ASR to ensure long-term performance of ASR-affected structures. Measures to prevent additional water penetration will have an unpredictable efficacy because there is no way to know how much more damage will be caused by the water already inside the concrete. This is because it is not possible to determine the degree of the reaction, from which to estimate future expansion from existing water. Attempts to dry out one side of a structure will hasten precipitation near the drying surface, which will concentrate the alkalis, resulting in accelerated ASR near the surface.

Options for managing the ASR reaction in existing concrete structures are limited. One approach is to stop, or significantly slow, the reaction. Because the reactive silica is in the aggregates, the remaining options are to starve the reaction of water or alkalis. Assuming that water is available from the environment, the use of water barriers is limited to structures for which the external surface is accessible. Reducing alkalis requires changing the pore water (flushing the concrete), which would likely ensure complete saturation of the concrete. This, in turn, may provide sufficient moisture to maintain the reaction for a number of years.

One repair alternative is to fill existing cracks with a sealant such as epoxy, but the effectiveness of such an approach is difficult to quantify. If successful, this could flush out water that was in the cracks, and fill the cracks with an impermeable material that would prevent additional water from entering the concrete. The overall success of this approach, however, may depend strongly on the moisture content of the concrete. If the concrete is saturated with water, the epoxy will not displace the large quantity of water in the cement paste, and the reaction will continue. If there is sufficient water that additional cracking occurs, these cracks will form new avenues for additional water to enter the concrete.

It may also be difficult to quantify the efficacy of drying the concrete element at the internal surface when the external surface is exposed to moisture, as this may also cause problems. Just below the internal surface of the concrete there will be a drying front at which the moisture in the concrete transitions to vapor. At this transition point, the alkalis in the pore solution will be a maximum, which could further drive the ASR reaction. With a constant source of moisture on the external surface, transport through the element will continue to supply additional alkalis to the drying front. Complex heat and moisture transport models are needed to determine whether such an approach is beneficial or not.

Any approach to managing the effects of ASR on structural concrete will require some means of assessing the structural properties of the concrete because of the evidence that cracking in general, and ASR specifically, can reduce the capacity of structural concrete elements. Therefore, a lack of methods for evaluating the structural properties would be a serious gap in the ability to develop a comprehensive aging management plan. Furthermore, if there are no tools or tests that one can use to predict the rate of degradation, one will have to incorporate a higher rate of inspection (with respect to the rate of inspection of concrete without degradation).

3.6 Numerical Modeling of ASR

No reliable models exist for simulating alkali-silica reactions at the microscopic length scale. Moreover, there is still debate on whether the gel forms at the surface of the aggregate or whether silica species diffuse through the pore solution and react with other dissolved species within the pores. Furthermore, details of the reaction may depend on the chemical nature of the specific reactive phase; there are numerous possible reactive phases to consider.

None of the numerical models for the alkali-silica reaction are directly applicable to assessing the condition of an existing structure. The models are typically "expanding sphere" models that require a relatively large number of material properties of the undamaged concrete.

3.7 ASR Prevention During New Construction

There are no reliable test methods or industry best practice guides for testing and qualifying materials that may be sufficiently immune to ASR for 75 years to 100 years. Current test methods, such as the accelerated mortar bar test and the concrete prism test, and the acceptance performance criteria that are often required from this testing, were developed to assure reliable performance in concrete structures that would be in service for only 50 years to 75 years. Presently, the most up-to-date guide is the AASHTO PP 65 standard practice (Thomas et al. 2012c, Thomas et al. 2012d).

3.8 Effects of ASR-Induced Cracking on Transport Properties

Much is still unknown about the specific effects of cracks on transport properties, for any degradation mechanism. The challenge with ASR is that expansion occurs wherever the reaction occurs, so the cracks tend to be distributed throughout the concrete. Furthermore, the cracking can be altered significantly as a result of the amount and the orientation of steel reinforcement.

The cracking that occurs from extensive ASR can provide pathways for fluid transport through the concrete. If the concrete structure is located in a region with brackish water, infiltrating groundwater could accelerate the rate of corrosion in reinforced concrete. For degradation mechanisms that depend upon diffusion (e.g., corrosion of the reinforcement, sulfate attack), any water-filled cracks will accelerate the rate of diffusion.

The degree to which the cracking will accelerate degradation depends on the nature of the cracking and the degradation mechanism. If cracks are "finely" distributed, they contribute to the overall bulk transport through the concrete. If cracks are long and oriented, the cracks in proximity to individual reinforcement elements may play a far greater role in influencing the rate of corrosion than cracks farther away from the reinforcement.

For "finely" distributed cracks, one can approximate the overall effect by characterizing the relative change in the bulk transport property. Because for saturated concrete relative changes in diffusivity are (nearly) proportional to relative changes in electrical conductivity, a doubling of the electrical conductivity would suggest there is a commensurate doubling of the diffusivity. Therefore, either buried or surface electrodes could be used to monitor changes in the transport properties.

For wide cracks oriented parallel to the transport direction, a slightly different strategy is needed, but one that still relies upon exploiting the relationship between conductivity and diffusivity. The change in the diffusivity of the cover concrete is equivalent to the change in conductivity. Therefore, measuring changes in the electrical conductivity between the outside surface and the reinforcement should give a meaningful indication of the effect of the large oriented cracks on the rate at which dissolved species like chlorides will diffuse to the reinforcement. Again, this is valid provided conductivity is measured when the concrete is saturated.

The challenge in using these electrical methods is accounting for the differences in the electrical conductivity of the pore solution in the hardened paste and the electrical conductivity of the solution in the cracks. As a first approximation, one could approximate the contents of the cracks by the groundwater composition.

3.9 Summary

This section addressed current gaps in our understanding of the performance of ASR-affected concrete. The primary gaps include (1) the inability to estimate the extent and rate of the chemical reaction without having historical data; (2) the inability to estimate the *in-situ* strength of the concrete; and (3) the inability to estimate quantitatively the effects of the ASR-induced cracking on transport (and other degradation mechanisms). Chapter 4 provides a recommended research plan to address the gaps identified in this chapter.

4 TECHNICAL PLAN

The strategies for evaluating existing concrete construction affected by ASR are based on the assumption that relatively little historical data exist for either the expansion exhibited by specific structural elements or the relevant material properties of the materials used during construction. Furthermore, separate plans are given for evaluating the existing properties of concrete and for estimating future properties of the concrete.

4.1 Articulated Priorities

The technical plan required to meet all the objectives addressed in Section 4.2 will be composed of a number of tasks, with each task contributing to one or more of the objectives. The technical plan in this chapter is developed to address these objectives assuming the following priority order as determined by NRC:

1. Identifying and evaluating method for managing the effects of ASR to maintain intended functionality
2. Identifying criteria to assess the state of the ASR with respect to structural performance
3. Identifying and evaluating methods for determining the state and severity of the ASR degradation, and for predicting the rate at which the reaction is progressing
4. Identifying the effects of ASR on the capacity of anchorages
5. Identifying and evaluating methods for determining the impact of ASR on the mechanical properties of reinforced concrete as they relate to the static and dynamic performance
6. Identifying parameters to be measured and the criteria to be used to determine when the ACI 349 code provisions and other related standards and codes may not be valid
7. Identifying data needed to develop reliable numerical models for the formation of ASR and for evaluating the performance of ASR-affected concrete.
8. Quantifying the change in transport processes through ASR-affected concrete and identifying how it may affect other degradation mechanisms such as corrosion of the steel reinforcement
9. Identifying standard test methods for new construction that may improve the effectiveness of reducing the likelihood of ASR.

As mentioned in Section 3.5, assessing the structural performance of a reinforced concrete element exhibiting distress due to ASR is an important component of a management plan. Therefore, the top two priorities are closely related. Furthermore, an aging management plan that includes a revised schedule for inspection and evaluation for affected concrete will require some means of understanding the rate of the ASR degradation. Therefore, a technical plan that focuses on developing tests for estimating the current and future structural properties will address the five highest priorities, and contributes to next two highest priorities.

4.2 Structural Capacity of Existing Structures

The Technical Plan for existing structures includes two objectives:

1. Determining the current structural capacity of an element
2. Estimating the future structural capacity of an element

The goal of the first objective is to develop a testing procedure that will yield reliable material property data for performing a structural evaluation of the current structure. The goal of the second objective is to develop a methodology for estimating the extent of the reaction over time, and building a relationship between the extent of the reaction and the changes in mechanical properties.

The plan is described briefly as follows:

1. Estimating the degree of confinement in ASR-affected reinforced concrete element using a linear elastic expansion.
2. Demonstrate that mechanical properties measured under confining stresses provide reliable parameters for evaluating existing structural capacity of the affected reinforced element.
3. Relate the resulting expansive forces to the extent of the reaction, via materials analysis and the extent of surface cracking, or both.
4. Develop a relationship between changes in the mechanical properties and a combination of the ASR-induced cracking and the confinement stress.
5. Create a model to estimate the future extent of ASR (including expansive forces and the extent of cracking).

4.2.1 Determine Structural Capacity of an Element

Objective: Validate an approach for estimating the structural capacity of ASR-affected reinforced concrete elements.

Overview:

1. Cast large-scale ASR-reactive reinforced concrete elements to represent common structural components, and embed tri-axial strain gauges at selected locations.
2. Perform a computational expansion analysis of the reinforced concrete element. Determine the degree of expansion that yield a strain distribution that best agrees with the strain gauge data.
3. Develop a reliable protocol for determining the extent of the reaction in an existing structure. This may include a combination of, test methods such as measurement of: surface cracking (e.g., CCI), mechanical tests (e.g., Stiffness Damage Test (SDT)), acoustic tests (e.g., acoustic emission, NIRAS), petrographic tests (e.g., mineral analysis, gel analysis), or image analysis of polished sections.
4. Validate the extent of the reaction to the expansive forces obtained from the expansion analysis.
5. Remove cores from the large-scale elements and perform compressive and tensile tests under tri-axial restraint consistent with the restraint indicated by the strain gauges. The expansion analysis will also be used to determine the ideal core orientation.
6. Relate the expansive forces and the internal confinement to the changes in the mechanical properties.

7. Validate that strengths measured under triaxial-stress conditions can be used to calculate reliably the element capacity by comparing to the direct measurements made on the large-scale specimens.

Deliverables:

- Protocol for estimating the extent of ASR, and the resulting volume expansion and corresponding forces.
- Methodology for using the expansive forces to perform an expansion analysis of a reinforced concrete element.
- Proposed standard test method for performing tri-axial tests to measure compressive and tensile strength under confined conditions.
- A method to estimate the mechanical properties of a concrete based on the degree of expansion and the degree of confinement.
- Methodology for determining ideal core orientation based on the expansion analysis.

For existing structures, use CCI data and a free-body expansion analysis to determine the degree of constraint everywhere; use analysis to guide core orientation planning. Remove cores and test under tri-axial restraint, based on expansion analysis. Use tri-axial test data to analyze the structure.

4.2.2 Recommended Plan for Assessing *In-Situ* Mechanical Properties of ASR-Affected Concrete:

Following the ACI 318 formulation (see Section 3.2), the splitting tensile strength (f_{ct}), the modulus of rupture (f_r) and the modulus of elasticity (E_c) can be expressed in terms of the compressive strength of concrete as shown in Equations (8), (9) and (10). Thus, if the compressive strength (f_c) of a given concrete and the numerical values of the coefficients A, B and C are known, the three mechanical properties of any concrete can be estimated for analysis of reinforced concrete structures.

$$f_{ct} = A\sqrt{f_c} \tag{8}$$

$$f_r = B\sqrt{f_c} \tag{9}$$

$$E_c = C\,w_c^{1.5}\,\sqrt{f_c} \tag{10}$$

To determine realistic *in-situ* compressive strength of concrete, the core samples taken from the existing structure should be tested under triaxial stress conditions that simulates the internal pressure produced by the ASR expansion that is restrained.

Because the direction of coring with respect to the direction of concrete placement affects the test results of specimens cores should be taken from the large block specimens in three orthogonal directions with respect to the orientation of the block specimen (see Figure 5).

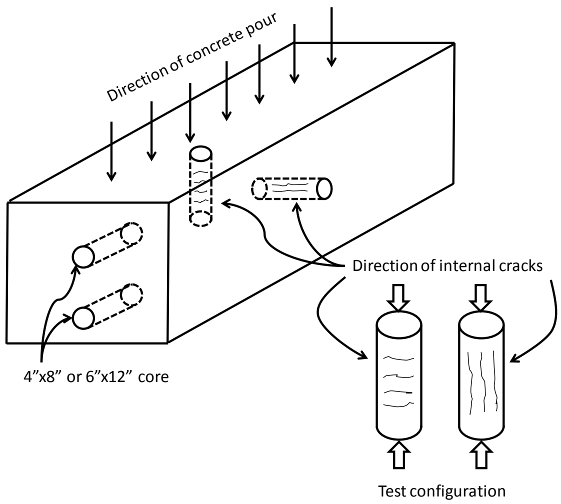

Figure 5. Direction of taking core samples

4.2.3 Estimating Future Mechanical Properties

Objective: Validate a relationship between changes in the extent of the reaction and changes in the mechanical properties of the concrete.

Overview:

1. Identify a test method for estimating the ultimate extent of the reaction. This is an asymptotic value of the expansion sigmoidal curve. This would be a two-step process. Laboratory test would be used to relate accelerated residual expansion tests values to ultimate expansion values. The relationship would then be validated on large specimens.
2. Develop a first-order kinetic model for estimating the future expansion, given information about the mixture design and the ultimate expansion. This model will likely require information about temperature and moisture dependence, and may require coupling to physicochemical service life computer models for concrete that can simulate both heat and moisture transport.

The first-order power-law approach may be a middle ground that balances simplicity and accuracy. This approach identifies the major contributing factors to ASR and uses physical or chemical knowledge to make first-order assumptions about the contribution of that factor to the overall rate of the reaction or degradation. Such an approach may be sufficiently accurate for determining the decade during which a structure may not have sufficient structural capacity. In such a case, one might then use a more rigorous monitoring strategy as the structure nears the predicted decade.

Deliverables:

- Test method for estimating the ultimate expansion.
- Develop a monitoring strategy where estimated percentages of the change in structural capacity could be used to determine the periodicity of coring and testing for verification.

4.2.4 Predicting the Effect of ASR on Bond and Anchorage

The following two types of tests are required to assess the anchorage of reinforcing bars in concrete which will affect the required length of lap splices and the anchorage length required to develop the yield strength of reinforcing bars.

1. Flexural tests with four-point loading using beams that have undergone various stages of ASR expansion. The test specimens are prepared with various lengths of lap splices in the constant moment region.

2. Pullout tests of single bars embedded in concrete specimens that have undergone various levels of ASR expansion. The bar diameter and embedment length are varied to determine the effect of ASR expansion on the anchorage strength.

4.2.5 Methodology for Assessing Response Characteristics of ASR-Affected Structures to Earthquake Loads

In earthquake prone regions, structures experience lateral movement due to ground shaking. To avoid sustaining serious damage, structures are designed such that the lateral displacement of vertical members (such as columns and walls) and the end rotation of horizontal members (such as beams and girders) would not exceed the allowable values. If the stiffness and energy absorbing capacity are reduced due to ASR, the response of structural members to earthquake excitation may exceed the design limits, thereby making the structure susceptible to serious damage or collapse during a design level earthquake. To assess the structural response of ASR-affected concrete members to the cyclic loading generated by an earthquake, the following properties are needed:

1. Compressive and tensile strengths and the modulus of elasticity of the concrete,

2. Reinforcing bar anchorage under cyclic loading, and

Energy absorption properties of members and connections under cyclic loading.

4.3 Effect of Cracking on Fluid Transport

Although it is understood that cracks increase the average rate of fluid transport through concrete, the specific manner in which distributed cracks contribute to transport is still largely unknown. Test methods are needed to characterize the overall effect of cracks on transport properties. These tests must also address the degree of saturation within the cracks.

1. Identify viable test methods for characterizing the effects of cracks on transport properties. These tests may include measurement of electrical properties on the surface or through the laboratory specimens or specimens extracted from the structure..

2. Validate the test method as a means of providing concrete service life estimation tools with information for modifying transport coefficients to account for the cracking present.

When ASR-affected concrete structures with surface cracks are exposed to aggressive conditions (such as chlorides and carbonation), their service lives are impaired due to corrosion of reinforcing steel. In addition, corrosion-induced stresses may further widen surface cracks. Thus it is important to determine the current rate of corrosion of reinforcing steel.

1. Detection of corrosion activity in reinforced concrete structures.

2. Measurement of corrosion rate in existing concrete structure using techniques such as the linear polarization resistance method (ASTM G59, ASTM G102).

5 SUMMARY

Evaluating the structural capacity of existing concrete structures exhibiting distress due to alkali-silica reaction (ASR) is a challenging problem. There are three primary reasons for this: the reaction rate is very slow; any observed expansion would be a function of the specific degree of restraint in the structure; and there is no test one can perform that can quantify the extent of the reaction. The first two reasons impact efforts to determine the present capacity, and the third reason impacts efforts to determine the future capacity.

The relatively slow rate of the reaction in concrete may require decades before the concrete exhibits distress at the surface. The slow rate of the reaction is an indication that there are many factors that contribute to ASR, and the variability in the rate of reaction reflects the variation in the properties of the concretes and their exposure conditions. When studying ASR in the laboratory, the challenge is to study representative concretes in a reasonable time frame. To achieve measureable expansion in a reason period of time, one must modify the mixture in a fundamental way (e.g., different aggregate sizing, additional highly reactive aggregate, alkaline mix water). Doing so, however, risks creating a material that does not represent the mechanical and chemical properties of the concrete being evaluated.

One can make correlations between laboratory expansion measurements and tests of mechanical properties, but these tests are typically performed on specimens that differ from the field concrete in one or more fundamental ways. The implicit assumption is that the visco-elastic properties of the laboratory concrete are sufficiently similar to the field concrete that the correlations are reliable for evaluating the field concrete over time. Laboratory degradation-strength correlations are typically performed using the free expansion of laboratory specimens. In the field, the concrete is almost always constrained by steel reinforcement and the continuity of the structure. Therefore, expansion measured at the surface of the structure will not be equal to the free expansion that would be observed in an un-reinforced concrete element for the same extent of ASR.

For existing structures, the challenge of determining the structural capacity is even greater. The degradation-strength correlations for the in-place concrete do not exist. Therefore, one must extract specimens and test them. The challenge is that the cracks that form due to ASR have a finite size, and they grow in size over time. The strength measured on a concrete core is a function of the mechanical properties of the concrete, the size of the specimen, and the ratio of the typical defect (i.e. crack) size to the specimen size. For intact (no defects) concrete, the measured core strength can be used to evaluate structural capacity in accordance with design provisions in existing codes. For concretes with distributed cracking, the effects of the cracks on the structural capacity are not known, and there are no industry guides for evaluating the structural capacity of ASR-affected reinforced concrete elements.

Estimating the future performance of an existing concrete exhibiting ASR distress is an even greater challenge. In addition to the challenge of estimating the current structural capacity of the distressed structure, the engineer must predict the rate and extent of future distress. This task is all the more challenging because the reacting phases may not have been accurately characterized, the details of the reaction for a particular mineral phase may not be known, and cracking that occurs in concretes exposed to the environment will likely accelerate ingress of ionic species that may also influence the rate of the reaction. In addition to this, the ingress of external species may accelerate other degradation mechanisms (e.g., leaching, corrosion of the steel reinforcement, sulfate attack) that would also influence the structural capacity of a reinforced concrete element.

A technical plan has been proposed for addressing these challenges. The plan focuses on modifying the ACI 318 relationships for estimating tensile strength, modulus of rupture, and modulus of elasticity from the compressive strength of distressed concrete; these are critical parameters in a structural evaluation. The assumption is that these material properties decrease as a function of the degree of degradation, which is either the equivalent degree of free expansion or the extent of the chemical reaction. The structural testing consists of making large-scale specimens with reactive aggregate and measuring the mechanical properties and the expansion of these elements over time.

In concert with the mechanical testing, extracted specimens will be evaluated to determine the degree of the degradation. A number of tests for characterizing the degree of degradation will be considered: residual expansion tests, mechanical tests, and petrographic tests. By using a number of different concrete mixtures that are representative of those used in nuclear power plants, relationships will be developed between the degree of the reaction and the modification needed to the ACI 318 relationships for estimating mechanical properties required to evaluate structural capacity.

The remaining technical plan addresses numerical simulation of ASR degradation. Of the current approaches being used to estimate future properties of ASR-affected concrete, the one recommended here is a first-order kinetic approach that captures the contribution of the primary factors affecting the rate of ASR. Although the resulting model will not have the accuracy of more sophisticated models, it should provide general guidance for estimating the progression of the reaction with time. From this predicted extent rate of reaction, one can use the relationships developed from the mechanical testing for the ACI code parameters to evaluate the future structural capacity of a structure exhibiting distress due to ASR.

6 REFERENCES

Ahmed , T., Burley, E., and Rigden, S. (1999), The static and fatigue strength of reinforce concrete beams affected by alkali-silika reaction, *ACI Materials Journal,* Vol. 95, No. 4, pp.376-388.

Ahmed , T., Burley, E., Rigden, S. and Abu-Tair, A.I. (2003), The effect of alkali reactivity on the mechanical properties of concrete, *Construction Building Materials*, Vol. 14, pp.123-144.

Ahmed , T., Burley, E., Rigden, S. and Abu-Tair, A.I. (2003), The effect of alkali reactivity on the mechanical properties of concrete, *Construction Building Materials*, Vol. 14, pp.123-144.

Ballard, Z.J., Caires, W.S., and Peters, S.R. (2008), Alternate Mitigation Materials for Alkali-Silica Reaction (ASR) in Concrete, CDOT-2008-10, Colorado Department of Transportation, Denver, CO.

Bangert, F., Kuhl, D., and Meschke, G. (2004), Chemo-hygro-mechanical modeling and numerical simulation of concrete deterioration caused by alkali-silica reaction, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 28, pp. 689-714.

Bažant, Z. and Steffens, A. (2000), Mathematical model for kinetics of alkali–silica reaction in concrete, *Cement and Concrete Research*, vol. 30, pp. 419-428.

Ben Haha, M., Gallucci, E., Guidoum, A., and Scrivener, K.L., "Relation of expansion due to alkali silica reaction to the degree of reaction measured by SEM image analysis," *Cement and Concrete Research*, Vol. 37, pp. 1206-1214.

Bérubé, M.-A., Chouinard, D., Pigeon, M., Frenette, J., Boisvert, L., and Rivest, M. (2002a), "Effectiveness of sealers in counteracting alkali-silica reaction in plan or air-entrained laboratory concretes exposed to wetting and drying, freezing and thawing, and salt water," *Canadian Journal of Civil Engineering*, Vol. 29, 289-300.

Bérubé, M.-A., Chouinard, D., Pigeon, M., Frenette, J., Boisvert, L., and Rivest, M. (2002a), "Effectiveness of sealers in counteracting alkali-silica reaction in highway median barriers exposed to wetting and drying, freezing and thawing, and deicing salt," *Canadian Journal of Civil Engineering*, Vol. 29, 329-337.

Bektas, F., Turanli, L., and Ostertag, C.P. (2006), New approach in mitigating damage caused by alkali-silica reaction, *Journal of Materials Science*, vol. 51, pp. 5760-5763.

Bérubé, M.-A., Smaoui, N., Fournier, B., Bissonnette, B., and Durand, B. (2005), Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part III: Application to existing structures, *Canadian Journal of Civil Engineering*, Vol .32, pp. 463-479.

British Cement Association (1992), The Diagnosis of Alkali-Silica Reaction, British Cement Association, Telford Avenue, Crowthorne, Berks, ISBN 0 7210 1369 4, 44 pp.

Carles-Gibergues, A., Cyr, M., Moisson, M. and Ringot, E. (2008), A simple way to mitigate alkali-silica reaction, *Materials and Structures*, vol. 41, pp. 73-83.

Chana, P.S. (1988), Transport and Road Research Laboratory, Department of Transport, UK.

Chana, P.S. (1989), Bond strength reinforcement in concrete affected by alkali-silica reaction, Contract Report 141, Transport and Road Research Laboratory, Department of Transport, UK.

Chana, P.S. and Koroboski, G.A. (1991), Structural performance of reinforced concrete affected by alkali-silica reaction: Phase I, Contract Report 267, Transport and Road Research Laboratory, Department of Transport, UK.

Chana, P.S. and Koroboski, G.A. (1992), Structural performance of reinforced concrete affected by alkali-silica reaction: Phase II, Contract Report 311, Transport and Road Research Laboratory, Department of Transport, UK.

Charlwood, R., Scrivener, K., and Sims, I. (2012), Recent developments in the management of chemical expansion of concrete in dams and hydro projects – Part 1: Existing structures, Hydro 2012, Bilboa Spain, October 29-30.

Chrisp, T.M., Waldron, P., and Wood, J.G.M. (1993), Development of a non-destructive test to quantify damage in deteriorated concrete, *Magazine of Concrete Research*, Vol. 45, pp. 247-256.

Clark, B.A, Schwoeble, A.J., Lee R.J., and Skalny, J. (1992), Detection of ASR in opened fractures of damaged concrete, Cement and Concrete Research, vol. 22, pp. 1170-1178.

Clark, L.A. (1989), Critical review of structural implications of alkali-silica reaction in concrete, Transport and Road Research Laboratory, Department of Transport, UK, Contract CON/9951/65.

Cong, X.D., Kirkpatrick, R.J., and Diamond, S. (1993), Si-29 MAS NMR Spectroscopic investigation of alkali-silica reaction-product gels, *Cement and Concrete Research*, Vol. 23, pp. 811-823.

Deschenes, D.J., Bayrak, O., and Folliard, K.J. (2009), ASR/DEF-Damaged Bent Caps: Shear Tests and Field Implications, Technical Report No. 12-8XXIA006, University of Texas, Austin, TX, 258 pp.

Dent Glasser, L.S. and Kataoka, N. (1981), The chemistry of alkali-aggregate reaction, *Cement and Concrete Research*, Vol. 11, pp. 1-9.

Diamond, S. (1975), A review of alkali-silica reaction and expansion mechanisms. 1. Alkalis in cements and in concrete pore solutions, *Cement and Concrete Research*, Vol. 5, pp. 329-346.

Diamond, S., Barneyback, R.S., and Struble, L.J. (1981), On the physics and chemistry of alkali-silica reaction, *Proc. 5th Int. Conf. on Alkali-Aggregate Reaction in Concrete (ICAAR),* Cape Town, S252/22, pp. 1-11.

Drimalas, T., Folliard, K.J., Thomas, M.D.A., Fournier, B., and Bentivegna, A. (2012), "Study of the Effectiveness of Lithium and Silane Treatments on Field Structures Affected by ASR," Proceedings of the 14th International Conference on AAR (ICAAR), Austin, TX.

Dron, R. and Brivot, F. (1992), Thermodynamic and kinetic approach to the alkali-silica reaction. Part 1: Concepts, *Cement and Concrete Research*, Vol. 22, pp. 941-948.

Dron, R. and Brivot, F. (1993), Thermodynamic and kinetic approach to the alkali-silica reaction. Part 2: Experiment, *Cement and Concrete Research*, Vol. 23, pp. 93-103.

Dunant, C.F. and Scrivener, K.L. (2012), Effects of aggregate size on alkali-silica-reaction induced expansion, *Cement and Concrete Research*, Vol. 42, pp. 745-751.

Edvardsen, C. (1999), Water permeability and autogenous healing of cracks in concrete, *ACI Materials Journal*, Vol. 96, pp. 448-455.

Farny, J.A. and Kerkhoff, B. (2007), "Diagnosis and Control of Alkali-Aggregate Reactions in Concrete," Portland Cement Association, Skokie, IL, 26 pp.

Ferraris, C.F., Garboczi, E.J., Davis, F.L., and Clifton, J.R. (1997), "Effect of stress relaxation, self-dessication, and water absorption on alkali-silica reaction in low water cement ratio mortars," *Cement and Concrete Research*, Vol. 27, pp. 1553-1560.

Folliard, K.J., Barborak, R., Drimalas, T., Du, L., Garber, S., Ideker, J., Ley, T., Williams, S., Juenger, M., Fournier, B., Thomas, M.D.A. (2006), Preventing ASR/DEF in New Concrete: Final Report, FHWA/TX-06/0-4085-5, Texas Department of Transportation, Austin TX, 234 pp.

Fournier, B., Bérubé, M.-A., and Bergeron, G. (1991), "A rapid autoclave mortar bar method to determine the potential alkali-silica reactivity of St. Lawrence Lowlands carbonate aggregates," *Cement, Concrete, and Aggregates (CCAGDP)*, Vol. 13, pp. 58-71.

Fournier, B. and Bérubé, M.-A. (2000), Alkali-aggregate reaction in concrete: A review of basic concepts and engineering implications, *Canadian Journal of Civil Engineering*, Vol. 27, pp. 167-191.

Fournier, B., Bérubé, M.-A., Thomas, M.D.A., Smaoui, N., Folliard, K.J. (2004), Evaluation and Management of Concrete Structures Affected by Alkali-Silica Reaction – A Review, Report MTL 2004-11, CANMET Materials Technology Laboratory, 59 pp.

Fournier, B., Bérubé, M.-A., Folliard, K.J., and Thomas, M.D.A. (2010), Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures, FHWA-HIF-09-004, Federal Highway Administration, McLean, VA.

Ferguson, P.M. (1966), Bond stress-the state of the art, ACI Committee 408 Report, *Journal of American Concrete Institute*, November.

Godart, B., Sims, I., Nixon, P., Capra, B., de Rooij, M., and Wood, J. (2012), "The RILEM Guidance on Appraisal and Management of Structures Damaged by AAR," Proceedings of the 14th International Conference on AAR (ICAAR), Austin, TX.

Godart, B., de Rooij, M., and Wood, J. (2013), Guide to Diagnosis and Appraisal of AAR Damage to Concrete in Structures, RILEM State-of-the-Art Report Vol. 12, Springer.

Grattan-Bellew, P.E. and Mitchell, L.D. (2006), "Quantitative Petrographic Analysis of Concrete – The Damage Rating Index (DRI) Method, A Review," M.A. Bérubé Symposium on Alkali-Aggregate Reactivity in Concrete: 8th CANMET/ACI International Conference on Recent Advances in Concrete Technology, Montréal Canada.

Guthrie, G.D. and Carey, J.W. (1998), Geochemical Methods for the Identification of ASR Gel, LA-UR-98-3570, Los Alamos National Laboratory, Los Alamos, NM.

Hamoudi, A., Khouchaf, L., Depecker, C., Revel, B., Montagne, L., and Cordier, P. (2008), Microstructural evolution of amorphous silica following alkali-silica reaction, *Journal of Non-Crystalline Solids*, Vol. 354, pp. 5074-5078.

Hansen, W.C. (1944), Studies relating to the mechanism by which the alkali-aggregate reaction produces expansion in concrete, *Journal of the American Concrete Institute*, Vol. 15, p. 213-227.

Helmuth, R., Stark, D., and Diamond, S. (1993), Alkali-Silica Reactivity: An Overview of Research, SHRP-C-342, Strategic Highway Research Program, Washington, D.C., 106 pp.

Hobbs, D.W. (1986), Alkali-silica reaction in concrete, *The Structural Engineer*, Vol. 64A, No. 12, pp. 381-383.

Hurcomb, D. (2009), New Recommendations for ASR Mitigation in Reclamation Concrete Construction, MERL Report-09-23, Bureau of Reclamation, U.S. Department of Interior, Denver, Colorado, 20 pp.

Institution of Structural Engineers (ISE) (1992), Structural Effects of Alkali-Silica Reaction - Technical Guidance Appraisal of Existing Structures, Institution of Structural Engineers, 11 Upper Belgrave Street, London SW1X 8BH, 45 pp.

Jensen, A.D., Chatterji, S., Christensen, P., and Thaulow, N. (1984), Studies of alkali–silica reaction. Part II – Effect of air-entraining on expansion, *Cement and Concrete Research*, Vol. 14, pp. 311–314.

Jin, W.-H. (1998), Alkali–Silica Reaction in Concrete with Glass Aggregate - A Chemo-Physical–Mechanical Approach. PhD Dissertation, Columbia University, New York.

Kodjo, A.S., Rivard, P., Cohen-Tenoudji, F., and Gallias, J.-L. (2011), Impact of alkali-silica reaction products on slow dynamics behavior of concrete, *Cement and Concrete Research*, Vol. 41, pp. 422-428.

Laboratoire Central des Ponts et Chaussées (1997), “Méthode d'essai no. 47 - Détermination de l'indice de fissuration d'un parement de béton.” Ministère de l’équipement, des transports et du logement, 58 bd Lefebvre F75732 Paris cedex 15.

Lane, D.S. and Ozyildirim, H.C. (1995), Use of Fly Ash, Slag, or Silica Fume to Inhibit Alkali-Silica Reactivity, Report No. 95-R21, Virginia Transportation Research Council, 41 pp.

Lane, D.S. and Ozyildirim, C. (1999), Preventive measures for alkali-silica reactions (binary and ternary systems), *Cement and Concrete Research*, Vol. 29, pp. 1281-1288.

Leśnicki, K.J., Kim, J.-Y., Kurtis, K.E., and Jacobs, L.J. (2011), Characterization of ASR damage in concrete using nonlinear impact resonance acoustic spectroscopy technique, *Cement and Concrete Research*, Vol. 44, pp. 721-727.

Mainguy, M. and Ulm, F.-J. (2001), Coupled diffusion-dissolution around a fracture channel: The solute congestion phenomenon, *Transport in Porous Media*, Vol. 80, pp. 481-497.

Mather, B. (1999), "How to make concrete that will not suffer deleterious alkali-silica reaction," *Cement and Concrete Research*, Vol. 29, pp. 1277-1280.

McCoy, W.J., and Caldwell, A.G. (1951), New approach in inhibiting alkali–aggregate expansion. *ACI Journal*, Vol. 22, No. 9, pp. 693–706.

McLeish, A. (1990), Structural implications of the alkali-silica reaction in concrete, Contract Report 177, Transport and Road Research Laboratory, Department of Transport, UK.

Meyer, C. and Baxter, S. (1998), Use of recycled glass and fly ash for precast concrete. Report NYSERDA 98-18 (4292-IABR-IA-96) to New York State Energy Research and Development Authority, Department of Civil Engineering and Engineering Mechanics, Columbia University.

Natesaiyer, K. and Hover, K.C. (1988), Insitu identification of ASR products in concrete, *Cement and Concrete Research*, Vol. 18, pp. 455-463.

Naus D.J. (2007), Primer on Durability of Nuclear Power Plant Reinforced Concrete Structures - A Review of Pertinent Factors, NUREG/CR-6927, U.S. Nuclear Regulatory Commission, Washington, D.C., 112 pp.

Naus, D.J. (2011), Overview of activities in the U.S. related to continued service of nuclear power plant concrete structures, EPJ Web of Conferences, Vol. 12, 01001 (AMP 2010 – International Workshop on Ageing Management of Nuclear Power Plants and Waste Disposal Structures) http://dx.doi.org/10.1051/epjconf/20111201001

Orangun, C.O., Jirsa, J.O., and Breen, J.E., (1977), A re-evaluation of test data on development length and splices, *Journal of American Concrete Institute,* Vol 74, pp. 114-122.

Payan, C., Garnier, V., Moysan, J., Johnson, P.A. (2007), Applying nonlinear resonant ultrasound spectroscopy to improving thermal damage assessment in concrete, *Journal of the Acoustical Society of America*, Vol. 121, pp. EL 125-130.

PCA (2007), Guide Specification for Concrete Subject to Alkali-Silica Reactions, IS415, Portland Cement Association.

Pesavento, F., Gawin, D., Wyrzykowski, M., Schrefler, B.A., and Simoni, L. (2012), Modeling alkali-silica reaction in non-isothermal, partially saturated cement based materials, *Computer Methods in Applied Mechanics and Engineering*, Vol. 225-228, pp. 95-115.

Pleau, R., Bérubé, M.A., Pigeon, M., Fournier, B., and Raphael, S. (1989), Mechanical behavior of concrete affected by ASR. In *Proceedings of the Eight International Conference on Alkali–Aggregate Reaction in Concrete*, Kyoto, Japan, August 1989. *Edited by* K. Okada, S. Nishibayashi and M. Kawamura. pp. 721–726.

Powers, L.J. (1999), Developments in Alkali-Silica Gel Detection, Concrete Technology Today, PL991, Portland Cement Association, Skokie, IL.

Puatatsananon, W. and Saouma, V. (2013), “Chemo-mechanical micromodel for alkali-silica reaction,” *ACI Materials Journal*, Vol. 110, 67-77.

Ren, W. and Naus, D. (2012), Nuclear Concrete Materials Database Phase I Development, ORNL/TM-2011/296, Oak Ridge National Laboratory, Oak Ridge, TN, 24 pp.

Rigden, S.R., Majlesi, Y., and Burley, E. (1995), “Investigation of factors influencing the expansive behavior, compressive strength and modulus of rupture of alkali-silica reactive concrete using laboratory mixes.” *Magazine of Concrete Research*, Vol. 47, No. 170, pp. 11-21.

Rivard, P., Fournier, B., and Ballivy, G. (2002), The Damage Rating Index method for ASR Affected concrete – A critical review of petrographic features of deterioration and evaluation criteria, *Cement, Concrete, and Aggregates*, Vol. 24, No. 2, pp. 81-91.

Rivard, P. and Ballivy, G. (2005), Assessment of the expansion related to alkali-silica reaction by the Damage Rating Index method, *Cement and Concrete Research*, Vol. 19, pp. 83-90.

Saint-Pierre, F., Rivard, P., and Ballivy, G. (2007), Measurement of alkali-silica reaction progression by ultrasonic waves attenuation, *Cement and Concrete Research*, Vol. 37, pp. 948-956.

Sanchez, L., Fournier, B., Jolin, M. (2012). “Study of the parameters of the stiffness damage test for assessing concrete damage due to alkali-silica reaction,” Proceedings of the 14th International Conference on AAR (ICAAR), Austin, TX.

Saouma, V. and Perotti, L. (2006), “Constitutive model for alkali-aggregate reactions,” *ACI Materials Journal*, Vol. 103, pp. 194-202.

Saouma, V., Perotti, L., and Shimpo, T. (2007), “Stress analysis of concrete structures subjected to alkali-aggregate reactions,” *ACI Structural Journal*, Vol. 104, pp. 532-541.

Smaoui, N., Bérubé, M.-A., Fournier, B., Bissonnette, B., and Durand, B. (2004a), Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part I: Experimental study, *Canadian Journal of Civil Engineering*, Vol. 31, pp. 826-845.

Smaoui, N., Fournier, B., Bérubé, M.-A., Bissonnette, B., and Durand, B. (2004b), Evaluation of the expansion attained to date by concrete affected by alkali-silica reaction. Part II: Application to nonreinforced concrete specimens exposed outside, *Canadian Journal of Civil Engineering*, Vol .31, pp. 997-1011.

Smaoui, N., Bissonnette, B., Bérubé, M.A., Fournier, B., and Durand, B. (2006), Mechanical properties of ASR-affected concrete containing fine or coarse reactive aggregates, *Journal of ASTM International*, Vol. 3, No. 3, pp. 1-16.

Snyder, K.A. (2000), Effect of Drying Shrinkage Cracks and Flexural Cracks on Concrete Bulk Permeability, NISTIR 6519, National Institute of Standards and Technology, Gaithersburg, MD.

Snyder, K.A. (2001), The relationship between the formation factor and the diffusion coefficient of porous materials saturated with concentrated electrolytes: Theoretical and experimental considerations, *Concrete Science and Engineering*, Vol. 3, pp. 216-224.

Stanton, T.E. (1940), Expansion of Concrete Through Reaction Between Cement and Aggregate, Proceedings, American Society of Civil Engineers, Vol. 66, p. 1781-1811.

Stark, D. (1991), Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures, SHRP-C/FR-91-101, Strategic Highway Research Program, Washington, D.C. Also PCA Publication LT165.

Swamy, R.N.,Al-Asali, M.M. (1988), Engineering properties of concrete affected by alkali-silica reaction, *ACI Materials Journal,* Vol. 85, No. 5, pp. 367-374.

Tang, M.-S., Han, S.-F, and Zhen, S.-H (1983), "A rapid method for identification of alkali reactivity of aggregate," *Cement and Concrete Research*, Vol. 13, pp. 417-422.

Taylor, H.F.W. (1990), *Cement Chemistry*, Academic Press, New York.

Thomas, M.D.A., Fournier, B., Folliard, K., Ideker, J. and Shehata, M. (2006), Test Methods for Evaluating Preventive Measures for Controlling Expansion due to Alkali-silica Reaction in Concrete, *Cement and Concrete Research*, Vol. 36 (10), pp. 1842-1856.

Thomas, M.D.A, Fournier, B., and Folliard, K.J. (2008), Report on Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction, FHWA-HIF-09-001, Federal Highway Administration, McLean, VA.

Thomas, M.D.A, Fournier, B., Folliard, K.J., and Resendez, Y.A. (2012a), Alkali-Silica Reactivity Field Identification Handbook, FHWA-HIF-12-022, Federal Highway Administration, McLean, VA, 69 pp.

Thomas, M.D.A, Fournier, B., Folliard, K.J., and Resendez, Y.A. (2012b), Alkali-Silica Reactivity Surveying and Tracking Guidelines, FHWA-HIF-12-046, Federal Highway Administration, McLean, VA, 30 pp.

Thomas, M.D.A, Folliard, K.J., Fournier, B., and Ahlstrom, G. (2012c), "A Prescriptive Specification for the Selection of Measures for Preventing Alkali-Silica Reaction," Proceedings of the 14th International Conference on AAR (ICAAR), Austin, TX.

Thomas, M.D.A, Fournier, B., and Folliard, K.J. (2012d), Selecting Measures to Prevent Deleterious Alkali-Silica Reaction in Concrete: Rationale for the AASHTO PP65 Prescriptive Approach, FHWA-HIF-13-002, Federal Highway Administration, McLean, VA, 47 pp.

Ulm, F.-J., Coussy, O., Kefei, L., Larive, C. (2000), Thermo-Chemo-Mechanics of ASR expansion in concrete structures, *Journal of Engineering Mechanics*, Vol. 126, pp. 233-242.

Van der Meer, J.J., (1979), An investigation into the bond splitting effect of deformed reinforcing bars, Master of Engineering Thesis, University of Western Australia.

Walker, H.N., Lane, D.S., and Stutzman, P.E. (2006), Petrographic Methods of Examining Hardened Concrete: A Petrographic Manual, FHWA-HRT-04-150, Federal Highway Administration, McLean, VA.