

A Crack Is Not a Crack: Alkali-Silica Reaction- Induced Cracking

by Dr. Oguzhan Bayrak, University of Texas at Austin

This article, which is the seventh article in this series, focuses on cracking induced by alkali-silica reaction (ASR) and the structural implications of ASR-related cracks. Let us start by acknowledging that stewardship of our concrete bridges is receiving significant national attention—and rightfully so. We have come a long way since the days of the initial development and implementation of the Dwight D. Eisenhower National System of Interstate and Defense Highways. Starting with that effort in the 1950s, we have built a network of controlled-access highways in the United States. As the concrete bridge industry continues its work to expand, improve, and build upon our established system of highways, a key priority is to maintain the existing inventory of our bridges with consideration for public safety and the responsible use of resources. Within this context, the structural evaluation of bridges affected by ASR is a significant challenge. To address this challenge for all concrete structures (not just bridges), *fib* (International Federation for Structural Concrete) published a groundbreaking structural evaluation guideline within the *Model Code for Concrete Structures 2020* (MC 2020).¹ The objective of MC 2020 is to provide uniform guidance for the design of new structures and the evaluation of existing structures. This article will reference MC 2020 recommendations to draw the attention of the concrete bridge community to MC 2020 and the benefits it offers for the structural evaluation of ASR-affected concrete bridges.

Context: What Is Alkali-Silica Reaction?

ASR is a chemical deterioration mechanism that affects concrete structures; it is a particular concern in those structures that were built before our current knowledge on this issue

was developed. In general terms, ASR occurs when reactive aggregates and an alkali pore solution in concrete form a hygroscopic gel as a reaction product. By its very nature, this reaction product expands as it absorbs water. At some point when the expansive pressures internal to concrete reach the tensile strength of concrete, the concrete element will develop ASR cracks. Figure 1 shows a generic example of ASR cracking. For new construction, the use of fly ash (as approximately 25% of cementitious materials) within the concrete mixture

and other mitigation techniques offer effective ways to manage reactive aggregates. By using an appropriate dosage of fly ash, we can mitigate expansion and cracking due to ASR. For older structures, we must have effective ways to identify the presence of ASR and evaluate its structural implications.

Expansion Mechanics

ASR is a bulk expansion mechanism. In other words, ASR-affected concrete tends to expand in all directions during this chemical process. Research performed

Figure 1. Cracking related to alkali-silica reaction (ASR) in a cube that is reinforced in one direction (into the page). The specimen was cast in 2015, and the photo was taken in 2023 as part of long-term monitoring of ASR-affected reinforced concrete cubes. Photo: Concrete Bridge Engineering Institute.



at the Ferguson Structural Engineering Laboratory at the University of Texas at Austin investigated the mechanics of ASR-affected concrete restrained in a variety of ways.² Highlights of the findings regarding the structural behavior of ASR-affected concrete are summarized herein:

- Unrestrained (plain) concrete expands in all directions almost uniformly, although slightly greater levels of expansion may be observed in the direction that the concrete was cast. Setting this subtlety aside, randomly oriented ASR cracks result in expansion in all directions. This expansion mechanism leads to severe degradation of the mechanical properties of concrete. Free expansion levels of 0.4% to 0.5% may reduce the compressive strength, tensile strength, and modulus of elasticity of concrete up to approximately 40% to 60%.¹ The cracking patterns in plain concrete samples are reasonably uniform and are frequently referred to as “map cracking.”
- Concrete restrained by the presence of reinforcement in one, two, or three directions expands differently than plain concrete. The presence of reinforcement in one direction serves to restrain expansion in that direction. Figure 1 shows the side of an approximately 19 in. cube that is not restrained within the plane of the photograph but is restrained by the cast-in deformed reinforcement (with machine-cut threads visible at the plates) placed in the perpendicular direction (that is, into the page). The restraint in one direction results in reduced expansion in the same direction (not visible in Fig. 1). Similarly, the presence of reinforcement in two directions creates a preferential expansion in the direction that lacks reinforcement. For example, in bridge decks, the preferential expansion direction would be the direction of gravity because bridge decks do not have through-thickness reinforcement. If there is reinforcement in all three directions, concrete benefits from the confining effects in all directions and cracking observed in such cases tends to be far less severe. Note that external restraints (for example, rigid supports) provide a similar effect.

With consideration given to the differences observed in free and restrained expansions, MC 2020 provides a comprehensive guideline that can be useful in conducting structural evaluations for concrete bridge components and therefore overall evaluation of the bridges themselves.

Diagnosis

As previously discussed, and as shown in Fig. 1, ASR-affected structures commonly display map cracking. The observed cracking pattern is influenced by internal (reinforcement) and external, boundary restraint conditions. In addition to map cracking, in some cases, ASR-gel exudation, dark reaction rims, and other features of ASR may be apparent on the surface. Observing such crack patterns and ASR features is the starting point of structural evaluation. Ultimately, petrographic analysis is necessary to identify the root cause of such cracking, as there are other conditions such as restrained shrinkage and delayed ettringite formation (DEF) that may result in similar cracking patterns. (See the Summer 2018 and Spring 2019 issues of *ASPIRE*[®] for in-depth information on ASR and DEF.)

To this end, MC 2020 states:

Presence of ASR gel in hardened concrete, as observed in petrographic analysis, is necessary. However, this condition is not sufficient to attribute distress to ASR. Cracking observed in the microstructure of concrete should be tied to ASR gel pockets and expansions observed by those gel pockets. It is possible to identify some ASR gel in many concrete structures but presence and extent of ASR may or may not be sufficient to cause distress (i.e., cracking) observed in the structure.

MC 2020 also states:

ASR-affected structures shall be diagnosed by using petrographic analysis. A representative number of cores shall be extracted from affected portions of the structure under investigation and a petrographer shall examine the cores to positively identify the root cause of the degradation mechanism as being ASR.

After ASR is positively identified, it becomes necessary to conduct an extent-

of-condition analysis. This analysis will result in grouping various locations and components in the bridges based on their levels of ASR damage, ranging from no ASR degradation to mild, moderate, and severe levels of ASR degradation. In this way, a formal methodology can be established for subsequent actions.

Monitoring Bridges Affected by Alkali-Silica Reaction

A plan should be developed to monitor the expansion behavior of the key structural components, in particular those components displaying high levels of ASR degradation and those with low levels of excess design margin. With regard to monitoring, MC 2020 specifies the following:

ASR-affected structures shall be monitored to identify and quantify progression of damage. Monitoring expansions and/or engineering strains in three principal directions is necessary to inform validity to the structural evaluations performed. ... Use of crack indexing, mechanical measurements, mechanical property degradation to estimate expansions in one or more directions under consideration shall be permitted.

Structural Evaluation of Bridges Affected by Alkali-Silica Reaction

MC 2020 adopts a framework of analysis known as Levels of Approximation (LoA). This approach is useful to calibrate the amount of engineering effort deployed in structural evaluation for a particular case. LoA I represents the most conservative analysis, and LoA IV is the most rigorous, time-consuming analysis.

The MC 2020 recommendations for the structural evaluation of ASR-affected structures are as follows:

LoA I analysis can be performed by making conservative assumptions. In this level of approximation, the most damaged location in the structure can be assumed to represent all areas of the structure and the impact of ASR on structural performance can be performed on the basis of this assumption. The use of linear and nonlinear analysis techniques to estimate the additional demands imposed on structural components can be deemed

appropriate by the engineer provided that the objectives of structural analysis are consistent with the simplifying, albeit conservative, assumptions made. The method of analysis chosen by the structural engineer has to be benchmarked against experimental data available in the literature. For the purpose of benchmarking large-scale tests should be preferred over small-scale tests, since large-scale specimens will be less impacted by alkali leaching and surface effects seen in all experimental programs that focused on ASR.

LoA I analysis typically provides overly conservative estimates of demands and capacities. In some cases where the structural design is not governed by load application, LoA I analysis may prove to be satisfactory to ensure structural adequacy. If such is not the case a more refined analysis (LoA II) can be performed. In this level of approximation, a thorough mapping of ASR cracks and identification/classification of areas with varying levels of ASR damage will be necessary. Portions of the structure subjected to water ingress or exposure to high levels of relative humidity are likely to display greater levels of ASR damage, i.e. ASR-induced expansions. The severely-, moderately-, and slightly-damaged portions of the structure should be modelled in such a manner that different expansions/displacements can be imposed on different parts. This level of refinement is likely to reduce demands imposed on the structure by ASR, as it provides a more realistic approximation between a numerical model and actual structure experiencing ASR-damage. Once again, equivalent linear or nonlinear techniques can be employed depending on the primary objectives of analysis.

LoA III analysis necessitates modelling the interaction between the expanding concrete and reinforcement explicitly, in addition to making accommodation for variation of ASR damage throughout the structure. This level of refinement is only justified in checking portions of a structure to check reinforcement yielding or in areas of low structural margin to gain improved insights on the reinforcing cage, ASR-damaged concrete interaction.

LoA IV analysis is the highest level of analysis possible to get the best

estimate, albeit with the least level of conservatism implicit in structural analysis. This level of refinement requires modelling nonlinear material response of concrete, reinforcing bars, and effects of confinement explicitly and through experimentally-verified models. Computational effort required by this level of refinement may or may not be justified depending on the cost of the required structural retrofits. In other words, it may be simpler and more cost-effective to deploy structural retrofit than try to conduct LoA IV analysis, given the need for experimental verification or benchmarking.

To explore the LoA approach, let us take a case from a research study completed at the Phil M. Ferguson Structural Engineering Laboratory in 2009.³ In that study, the shear strength of reinforced concrete bent caps with details that comply with the American Association of State Highway and Transportation Officials' AASHTO LRFD Bridge Design Specifications⁴ was evaluated for short (strut-and-tie method shear) and long (beam shear) shear spans. Interested readers are encouraged to read the complete report. To better understand the MC 2020 recommendations, let us consider the compressive strength of the concrete obtained by testing cores extracted from specimens nR1 (no ASR) and R2 (with ASR). The compressive strengths of concrete in nR1 and R2 were 7.2 ksi and 4.2 ksi, respectively. Importantly, ASR expansions caused shear reinforcement to yield (strain = 0.63%) before testing. Without the benefit of the large-scale test results, we may conclude that the shear strength of the bent cap must have been compromised by substantial reduction in the compressive strength of concrete and stirrups that yielded due to ASR expansions before load testing. As can be seen in the test results (Fig. 2), the structural capacity (that is, the shear strength) is "not compromised." That is to say, the load-carrying capacity of the specimen with ASR degradation is higher than the capacity of the specimen without any ASR damage. However, as a structural engineer, I would recommend ignoring any additional capacity observed in the specimen damaged by ASR or any other active degradation mechanism. This observed behavior can be explained by taking a deeper look

into the core testing. Triaxially confined concrete within the structural core of a bent cap behaves quite differently within its structural context than it does after that structural context is altered through coring. After the core sample is extracted from the bent cap, it loses the confining stresses that are present within the structure. Understanding this behavior helps us make decisions in the structural evaluation process. Importantly, if we were to use the compressive strength of unconfined cores directly with the expressions for shear strength in the AASHTO LRFD specifications, we would calculate greatly reduced capacities—which would be in conflict with the observed behavior summarized in Fig. 2.

The test results presented in Fig. 2 show that there is no adverse impact of ASR on the shear strength of the bent caps discussed in this example. For the ASR-expansion levels tested within the beam R2, ASR did not reduce the shear strength. This observation can simply be used in an LoA I or II analysis. Alternatively, it is also possible to use nonlinear finite element analyses, bring the interaction between the ASR-expansions and reinforcing cage into the picture, reduce the compressive strength of unconfined concrete substantially (from 7.2 ksi to 4.2 ksi in this case), and numerically restore the structural context (that is, explicitly account for the confining stresses imposed on ASR-affected concrete numerically within the analysis). When done properly, the results should match the observed experimental behavior. This type of approach takes us toward LoA III and IV analyses. In this example, leveraging the observed structural performance in a representative structural-scale test will drive the structural evaluation to an expedient conclusion. In more complicated cases, a detailed analysis could be appropriate. The LoA framework described within MC 2020 accommodates different approaches and emphasizes the importance of benchmarking. The example discussed herein highlights the importance of confinement. As long as the integrity of the reinforcing cage that is confining the ASR-affected concrete can be maintained, concerns over structural performance can be directly answered, as specified in MC 2020:

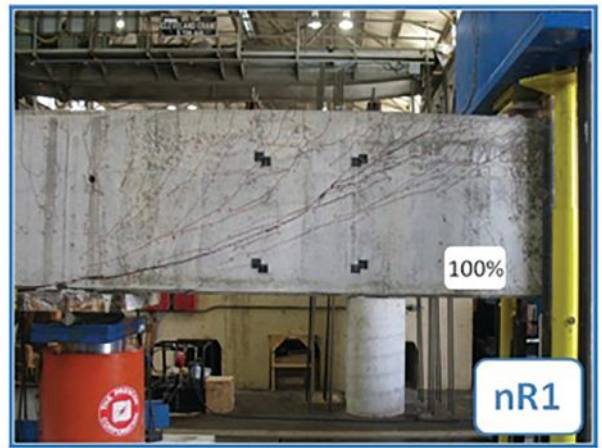
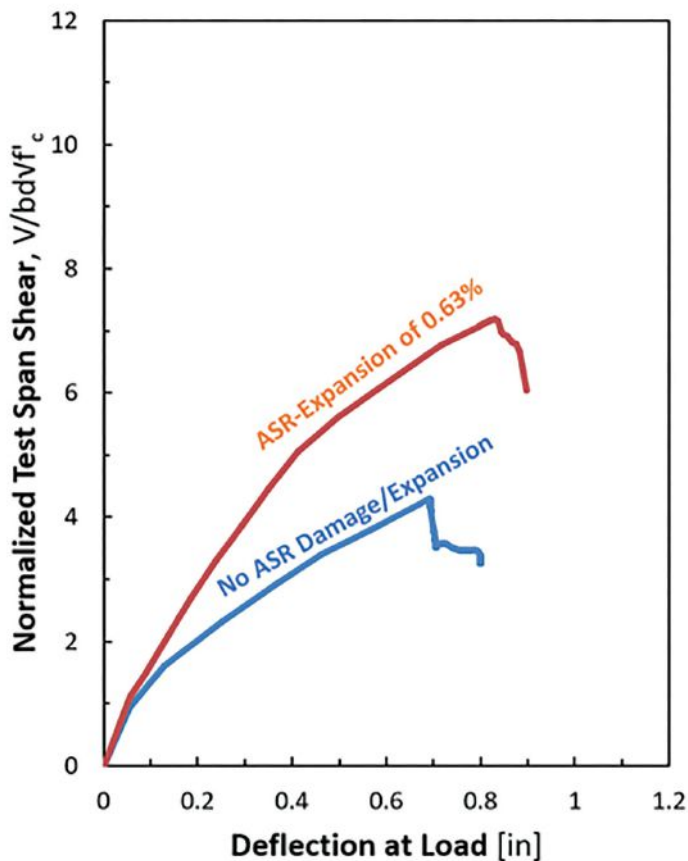


Figure 2. Load deflection behavior of a large-scale reinforced concrete bent cap specimen damaged by alkali-silica reaction (R2) compared with a control specimen (nR1).³ Figure: University of Texas at Austin.

The potential of reinforcing bar fracture in ASR-affected concrete structures shall be examined. If reinforcing bar bend diameters of the ASR-affected structures are in compliance with those of Model Code 2020, the potential of reinforcing bar fracture shall be taken as negligibly small.

This requirement in MC 2020 is informed by findings from the investigation of reinforcing bar fractures observed in Japan. Japanese researchers Imai et al.⁵ conducted a root-cause analysis and concluded that the tight mandrel diameters used in Japan, ASR expansions, and corrosion due to high chloride concentrations collectively led to the observed bar fractures. That is to say, the ASR expansion and the corrosion of carbon steel served as stressors on the “precracked” bar bends due to the tight mandrel diameters. MC 2020 addresses these field observations by suggesting that designers use the mandrel diameters recommended in MC 2020 (and American Concrete Institute, ASTM International, and AASHTO standards in the United States), as those diameters will render bar fracture at 90-degree bends to be a concern of a “negligibly small” magnitude.


Concluding Remarks

As discussed in this article, if ASR is identified to be the root cause of cracking, the MC 2020 recommendations can provide a formal approach to evaluate the appropriate condition analyses, structural monitoring, and structural evaluation processes. Understanding the root causes of cracking is paramount to developing solutions. Not all cracks are created equal. After all, a crack is not a crack.

References

1. fib (International Federation for Structural Concrete). 2020. *Model Code for Concrete Structures 2020*. Lausanne, Switzerland: fib.
2. Allford, M. T. 2016. “Expansion Behavior of Reinforced Concrete Elements Due to Alkali-Silica Reaction.” M.S. thesis, University of Texas at Austin. <http://hdl.handle.net/2152/41645>.
3. Deschenes, D. J., O. Bayrak, and K. J. Folliard. 2009. *ASR/DEF-Damaged Bent Caps: Shear Tests and Field Implications*. Technical report IAC-12-8XXIA006. Austin, TX: Center for Transportation Research, Bureau of

Engineering Research, University of Texas at Austin. <https://rosap.nrl.bts.gov/view/dot/17244>.

4. American Association of State Highway and Transportation Officials. 2007. *AASHTO LRFD Bridge Design Specifications*. 4th ed. Washington, DC: AASHTO.
5. Imai, H., T. Yamasaki, H. Maehara, and T. Miyagawa. 1989. “The Deterioration by Alkali-Silica Reaction of Hanshin Expressway Concrete Structures—Investigation and Repair.” In *Proceedings of the Seventh International Conference on Alkali-Aggregate Reaction*, Ottawa, ON, August 1987, edited by P. E. Gratten-Bellew. <https://icaarconcrete.org/wp-content/uploads/2024/04/7ICAAR-ImaiH-1.pdf>. 

EDITOR'S NOTE

Previous articles in ASPIRE have covered various aspects of alkali-silica reaction. For more information on this subject, see the Winter 2021, Fall 2020, Spring and Summer 2019, and Summer 2018 issues of ASPIRE.