MPC-583
December 14, 2018

Project Title
Composite Repair for Concrete Bridges Subjected to Alkali-Silica Reaction

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Research Needs
Concrete possesses alkali components such as sodium and potassium (Barneyback and Diamond 1981), which increase the potential of hydrogen (pH). When a high alkali condition of over pH = 12 encounters siliceous aggregates in concrete, durability problems arise. Upon the initiation of alkali-silica reaction (ASR), an amorphous gel forms around the aggregates and degrades the performance of structural members. If aggregates near a concrete surface are subjected to ASR damage, concrete spalling follows owing to the expansion of the ASR gel. The reinforcing bars are then directly exposed to aggressive environments, which will lead to a decrease in the strength and serviceability of the member. Federal Highway Administration recognizes that ASR is one of the major problems in highway infrastructure (FHWA 2011). While ASR-induced concrete deterioration typically takes place in 6 to 17 years of service (Palmer 1981), the time may be reduced when exposed to humid environments. The ingress of water into ASR gels brings about the swelling of the concrete (i.e., the absorbed water dissolves silica and accelerates chemical reactions through osmosis). If the tensile stress of ASR-activated concrete exceeds the modulus of rupture, irregular map cracking occurs, which is often observed in bridge members.

Multiple attributes influence the extent of ASR (Dyer 2014): alkali content, temperature, particle size and shape, moisture, and water-cement ratio. The amount of alkali content is traditionally represented by sodium oxide equivalent (Na_2O_{eq}). Temperature controls reaction rates between the alkali and silica (Carlos et al. 2004), whereas the degree of concrete expansion may not be a function of temperature (Neville 1995). Environmental cycling such as wet-dry worsens the durability of ASR-influenced concrete (Abdelrahman et al. 2016). Microscopy is a proven technique to detect the occurrence of ASR because dark-black gel layers surrounding aggregates can readily be observed in cored concrete (Fournier e tal. 2010). Micro-cracks resulting from ASR-induced expansion may be detected as well. From performance standpoints, the local bond failure between the aggregates and cement is another notable aspect of ASR damage in concrete. Rhyolite is a representative aggregate susceptible to ASR. As such, it is frequently exploited in test programs concerning ASR damage in concrete (Stark 1980; Sanchez et al. 2018). It is known that the size of grains influences the developmental rate of ASR (Diamond and Thaulow 1974).

Various methods have been in use to address the concerns associated with ASR damage in concrete members, including surface coating, lithium injection, and reinforced concrete jacketing ((Durand 2000; Thomas et al. 2013). Given that these approaches are effective for a limited number of years (Torii et al. 2004), long-term solutions need to be developed for the sake of the bridge engineering community. Recent research shows that composite-based repair is promising for ASR-damaged concrete members (Kubat et al. 2016). Carbon fiber-reinforced polymer (CFRP) sheets may enclose ASR-damaged concrete to enhance the load-carrying capacity and to preclude volumetric expansion. CFRP-wrapping can also restrict the ingress of external moisture into the concrete; consequently, detrimental chemical reactions in the concrete core are impeded. The use of such a non-corrosive repair material substantially improves the longevity of the repaired structure. Although repairing ASR-damaged concrete with CFRP composites appears an effective method, limited information is available for the practitioners to employ in the field. The current research program will explore the potential and feasibility of CFRP-based repair techniques for concrete members subjected to various levels of ASR damage.

Research Objectives

The objectives of the research are to:

- Quantify the deleterious effects of alkali-silica reaction (ASR) on the behavior of concrete bridges, particularly for axial load-bearing members
- Examine the efficacy of composite-based repair to improve the capacity of ASR-damaged concrete members
- Develop a theoretical model which can predict the performance of ASR-damaged and composite-repaired concrete members
- Propose design/practice recommendations for the implementation of the proposed composite repair method

Research Methods

The research program consists of experimental and analytical components at the material and member levels. The aforementioned objectives will be accomplished through scientific investigations into the complex interaction between ASR-damage and concrete retrofitted with composite sheets. Specific details are delineated as follows:

- *ASR-induced volumetric expansion in concrete*: ASR-reactive aggregates such as rhyolite will be mixed with concrete to accelerate ASR damage alongside sodium hydroxide. Narrow bars will be cast according to ASTM C1260 (*Standard test method for potential alkali reactivity of aggregates: mortar-bar method*). A relationship between the degree of ASR and the volumetric expansion of the concrete will be established to render important information on understanding the efficacy of composite-based repair for ASR-damaged concrete members.
- *Composite-based repair of ASR-damaged concrete*: concrete cylinders will be prepared with variable ASR-damage levels (rhyolite will be used for consistency), and retrofitted with carbon fiber reinforced polymer (CFRP) composite sheets. The specimens with and

without composite-repair will be loaded to examine the implications of ASR damage at the element level and to evaluate the degree of strength recovery resulting from the repair system.

- *Analytical investigations*: mechanical models will be formulated in accordance with test data. The mechanisms of concrete expansion and CFRP-induced confinement will be elucidated. Chemistry-assisted investigations are another possible approach in this task.

Practice recommendations and technology transfer: since ASR damage is frequent in constructed concrete bridges, a positive means to control this problem is necessary. All test data and model prediction will be integrated to develop practice guidelines for the benefit of the infrastructure community. Technology transfer will be immediate: conference presentations and technical articles in high quality journals.

Expected Outcomes

The two-fold research program consisting of test and modeling approaches will provide useful information to practicing engineers. The composite-based repair method will enhance the longevity of ASR-damaged bridge members, which have undergone cracking and spalling. The durability of these members will also be improved, because the composite sheets physically interrupt the ingress of detrimental chemicals into the concrete. The above-described recommendations will involve performance-based guidelines, rather than conventional prescriptive approaches. It is anticipated that the infrastructure community will benefit from this research by reducing maintenance effort with an increase in the service life of constructed concrete bridges.

Relevance to Strategic Goals

The theme of the regional University Transportation Center at North Dakota State University (Mountain-Plains Consortium) is '*Transportation Infrastructure and Operations to Support Sustainable Energy Development and the Safe Movement of People and Goods*', which aligns with the goal of the proposed research: developing a sustainable rehabilitation method to extend the longevity of existing concrete bridge members at affordable costs. Significant effort will be expended to address challenges associated with the nation's infrastructure. In addition, the primary interest of the current investigation meets the Secretary of Transportation's Strategic Goals (i.e., *State of Good Repair* and *Economic Competitiveness*).

Educational Benefits

Fostering next generation workforce is crucial from societal and technical perspectives. The research will train graduate students who will play an important role in bridge engineering. Findings will directly be used for the PI's graduate course entitled *Structural Rehabilitation* (CVEN5800), which was first offered in Fall 2017. The PI felt that technical contents related to ASR-induced damage and corresponding rehabilitation methods were relatively devalued in the course. The test results and modeling prediction as well as practice recommendations will enrich the course contents, so that graduate students and senior undergraduate students taking the course will benefit from this project.

Technology Transfer

Active technology transfer is planned through professional meetings, engineering conferences, and journal publications. The PI chairs a national technical committee in the American Concrete Institute (*FRP-prestressed Concrete*: ACI-440I) and has served as Chair of another committee (*Concrete Bridge Construction and Preservation*: ACI-345) from 2012 to 2018. The professional network developed by the PI will create synergies in disseminating research results. The PI is also the President of the Bridge Engineering Institute (BEI), an international technical society, and the Chair of an international bridge conference (BEI-2019) to be held in Honolulu, HI, in July 2019. It is expected that a number of bridge engineers and researchers will be attending from all over the world; accordingly, BEI-2019 will be an excellent venue for the PI to promote the research and the MPC program. Upon completion of the specific tasks, journal manuscripts will be prepared to broadly transfer scientific findings learned from the proposed project. In so doing, the state-of-the-art of bridge engineering will be advanced.

Work Plan

Task 1: Published literature will be collected in the area of ASR-damage and repair techniques. Although ASR damage is a common problem in concrete bridges, repair methods have not been advanced. The advantages and disadvantages of the existing methods will be assessed in comparison with the proposed composite-based approach. (Month 1-3)

Task 2: Pursuant to ASTM 1260 (*Standard test method for potential alkali reactivity of aggregates: mortar-bar method*), concrete prisms will be cast with rhyolite. Variable amounts of the ASR reactive aggregate will replace conventional aggregates. The specimens will be exposed to a sodium hydroxide solution, and time-dependent volumetric expansion will be measured to quantify the degree of ASR. Another test set will include CFRP-wrapped prisms for comparison. Statistical analysis will characterize the ASR behavior with and without the composite wrapping. (Month 4-12)

Task 3: After elucidating the characteristics of ASR damage, concrete cylinders will be prepared to expand the findings of Task 2. The rhyolite-replacement ratio will be maintained for consistency. The cylinders will be subjected to aggressive ASR conditions. One group of the deteriorated cylinders will be loaded to failure, while the other group will be repaired with CFRP sheets and then loaded. The axial responses of these two groups will comparatively be appraised with an emphasis on load-carrying capacity, strain development, and failure modes. (Month 13-20)

Task 4: Findings from Tasks 2 and 3 will be employed to develop practice guidelines. Of interest is to propose various performance levels, contingent upon the degree of ASR damage. This kind of information has not been published previously. (Month 21-24).

Project Cost

Total Project Costs:	\$100,000
MPC Funds Requested:	\$50,000
Matching Funds:	\$50,000
Source of Matching Funds:	faculty time and possible external scholarship/support awarded to participating individuals

References

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