Task 1 Report – Literature Review

Project Title: Alkali-Silica Reactivity in the State of Montana

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1 Introduction

Alkali-Silica Reactivity (ASR) is a deleterious reaction that takes place in concrete between alkalis present in the portland cement and reactive forms of silica in the aggregates. ASR can cause significant damage leading to reduced life span, costly repairs, and/or the replacement of the concrete. This damage is caused by the swelling (in the presence of water) of a gel that forms on the surface of the reactive aggregates, and typically results in map cracking similar to that shown in Figure 1. While ASR has been documented as an issue in many states, little work has been conducted to determine the presence/potential of ASR in Montana. The primary objectives of the proposed research are to evaluate the potential for deleterious ASR in the state of Montana, and to develop a testing protocol for identifying potential reactive aggregates. This research will also identify/document existing ASR damage in the state, and investigate the potential underlying geological features that may contribute to the presence of reactive aggregates.

The specific tasks associated with this research are as follows.

Task 1 – Literature Review

Task 2 – Determination of ASR Testing Protocol

Task 3 – Identify and Document Cases of ASR Damage in the State

Task 4 – Analysis of Results and Reporting

This report documents the work completed as part of Task 1 – Literature Review. It should be noted, that this literature review will continue to be updated as new research on this subject becomes available. This report first provides some background on ASR, and then discusses the ASR practices in surrounding states and within several federal agencies. It concludes with a brief summary of existing and newly developed ASR testing methods.

Figure 1: Typical ASR Crack Pattern

2 Background

ASR was first documented in 1940 in California [1]. Material testing methods were soon developed to assist in detecting reactive aggregates and to mitigate the potential of ASR in concrete. The initial ASTM specification developed to test for reactive aggregates failed to return consistent results, and led to the development of ASTM C1260 and ASTM C1293. Although the current methods are well accepted and used extensively in the concrete industry, these test methods have several shortcomings. ASTM C1260 offers a rapid test results, but is often cited as being overly conservative, and has sometimes been shown to return false negative/positive results [2]. ASTM C1293 has been shown to be more accurate/less conservative than ASTM C1260; however, its use in practice is hindered by the long duration of the test (at least one year). Due to these issues, recent research has focused on the development/evaluation of shorter duration/more accurate methods for testing for reactive aggregates. In conjunction with the development of testing standards, mitigation methods have also been developed/established to reduce the impact of ASR. These methods include the incorporation of supplementary cementitious materials (SCMs) in the concrete mixture (e.g., class F fly ash, silica fume, and natural pozzolans), and admixtures such as lithium.

While research on ASR in Montana is scarce, the research that has been conducted thus far indicates that some of Montana's aggregate sources are susceptible to ASR [3, 4]. In particular, Lawler and Krauss [4] tested four aggregate sources from geographically diverse areas in Montana, and found three of these aggregates to be reactive, with the fourth being somewhat reactive. They also demonstrated that the reactivity of these aggregates could be mitigated by the use of supplementary cementitious materials. The Montana Contractor Association (MCA) recently sponsored a project to establish a database of ASR tests that have been conducted in the state by various sources (e.g., aggregate suppliers, contractors, batch plants, and testing companies). In particular, ASTM C1260 and C1293 results were sought. However, the researchers in this investigation found that the majority of tests that have been conducted in the state have successfully included supplemental cementitious materials to mitigate potential ASR reactions. Thus, these tests were not useful in determining the underlying reactivity of the aggregates.

Despite the apparent potential for ASR in Montana, no cases of actual ASR have been documented in the state. The lack of documented cases may be due to several factors. First, cases may exist, but have not had an outlet for documentation. Further, ASR occurs in the presence of moisture and the relatively dry Montana climate may be preventing/reducing deleterious ASR. Finally, the use of supplementary cementitious materials and chemical admixtures, which have become more common in conventional concrete mixtures in the state of Montana, may be reducing the presence of ASR.

The following sections will discuss the state-of-the-practice, and recent advances in ASR detection/mitigation.

3 Regional and Federal ASR Practices

Reactive aggregates and the associated damage resulting from their use are known to be an issue in the region. Specifically, damage to hardened concrete due to ASR has been observed in all states adjacent to Montana [5], as can be seen in Figure 2. Additionally, results from ASR tests in the region have indicated that many aggregates have a moderate to high ASR potential [3, 6-8]. The following sections discuss the ASR practices of regional state departments of transportation, along with the practices of several federal agencies.

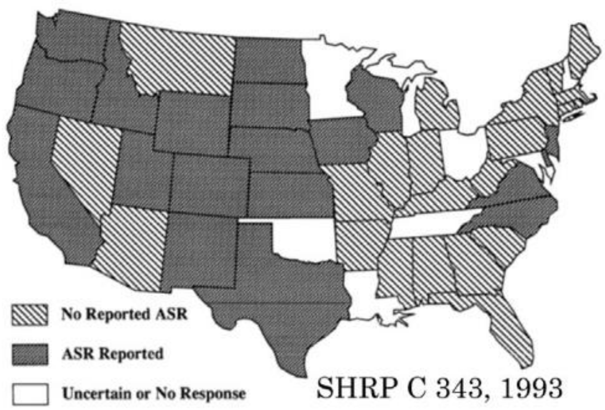

Figure 2: Occurrences of ASR in the United States [5]

3.1 Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) has fairly prescriptive methods for identifying and mitigating reactive aggregates in concrete, which are outlined in their material specifications [9]. In order to counteract ASR, independently of the aggregates used in the mix, WSDOT limits the alkali content in portland cement to 0.75% by weight as Na_2O. Further, if low alkali cement is required (based on the results of aggregate tests) the alkali content is limited to 0.6% by weight as Na_2O. Limiting the alkali content present in cement reduces the potential for ASR, while not requiring any special testing or batching with supplementary cementitious materials. However, the importance of determining aggregate reactivity in the concrete matrix is crucial in producing a non-deleterious mix.

In regards to aggregates, the specifications require that aggregates be tested per AASHTO T303/ ASTM C1260 by the WSDOT materials lab. If excessive expansions are observed, mitigation techniques (e.g., using fly ash, low alkali cement, lithium admixtures) are then prescribed for varying amounts of expansion. For aggregates with large expansions (over 0.45 percent), the mitigation method must be tested in accordance with ASTM C1567 to confirm the efficacy of the prescribed mitigation technique. Once tested, the aggregate source and test results are stored in the WSDOT Materials Lab's Aggregate Source Approval Database (https://www.wsdot.wa.gov/Business/MaterialsLab/ASA.htm) [8], where users can search available aggregate sources based on location and various selection criteria. In addition to the required ASTM C1260 tests, source owners can also opt to test their aggregates via the less conservative one -year ASTM C1293 test protocol.

3.2 Idaho Transportation Department

The material specifications of the Idaho Transportation Department (ITD) [10] require that concrete aggregates be tested for potential alkali silica reactivity using either AASHTO T303 (ASTM 1260), AASHTO TP110 (AASHTO T380), ASTM C1293, or ASTM C295. If deemed to be reactive, a mitigation technique must be approved by ITD and implemented. The efficacy of this mitigation technique must then be verified using ASTM C1567, AASHTO TP 110, or CRD C662.

In addition to addressing ASR in their material specifications, ITD has also recently sponsored several research projects focused on identifying potential reactive aggregates in Idaho [6, 11]. Gillerman and

Weppner [6] investigated the relationship between rock type and ASR with the intention of identifying geologic units that are more susceptible to ASR. As part of this research, they sampled 40 different aggregates (representative of the various rock types found in the state) and tested them for reactivity in accordance with ASTM C1260 and ASTM C1293. They found a clear correlation between ASR potential and mapped geology/specific rock types in Idaho, and developed maps documenting this correlation. Mishra and Kassem [11] are currently investigating the efficacy of using the newly developed and accelerated testing protocol AASHTO TP110 for evaluating the ASR potential of reactive aggregates. This testing protocol will be discussed in greater detail in a following section. This research is currently underway, with a final report due in December 2019.

3.3 North Dakota Department of Transportation

The standard material specifications for the North Dakota Department of Transportation (NDDOT) [12] do not specifically contain requirements regarding ASR testing. However, Monte Babok, the head of material testing division at NDDOT, was interviewed regarding NDDOT ASR procedures. During this interview Mr. Babock stated that, although ASR is not specifically addressed in the specifications, NDDOT does address it in some capacity. Specifically, when a concrete mix design using an unknown/questionable aggregate source is submitted to NDDOT for a project, ASR testing will be performed on the mix design to ensure ASR will not be an issue. While ASR is not known to be a major issue in North Dakota, there have been several documented cases of ASR damage in the past several decades [13, 14].

3.4 South Dakota Department of Transportation

The South Dakota Department of Transportation (SDDOT) has provisions in their material specifications that address ASR [15]. Specifically, they require all portland cement to have an alkali content less than 0.60% by weight total and conform to AASHTO M85. Regarding the aggregates, when specified in the plans, the fine aggregates are required to be tested in accordance to ASTM C1260 if the source has not been tested previously, or if the source has changed. Depending on the amount of expansion observed for the source, different mitigation techniques must be implemented. For expansions less than 0.25%, a Type II cement is required. For aggregates with expansions greater than 0.25% but less than 0.40%, a Type V cement is required, and aggregates with expansions greater than 0.40% are not permitted. It should be noted that the provisions do not permit other mitigation strategies (e.g., the inclusion of fly ash or admixtures) to reduce expansions. There are no provisions regarding course aggregates.

In regards to research on ASR, the SDDOT sponsored a research program in 2007 [16] that demonstrated the effectiveness of using lithium to mitigate ASR in new concrete and to mitigate the effects of ASR on existing pavements showing signs of ASR damage.

3.5 Wyoming Department of Transportation

The Wyoming Department of Transportation (WYDOT) material specifications [17] contains provisions that addresses ASR. According to the specifications, when required by the contract, AASHTO T303 (ASTM C1260) or ASTM 1567 (when fly ash is used) is required to be performed on a concrete mixture within 12 months of its use. The 14-day expansions on the concrete mixture must be less than 0.10%, if not, ASR must be mitigated through the use of class F fly ash, lithium compounds, or both.

In regard to research on ASR, WYDOT has sponsored several projects focused on the topic. Specifically, one recent project focused on testing aggregate sources from around Cheyenne, Wyoming, where aggregates have been determined to be reactive and problematic in the past [7]. This study used the ASTM C1293, ASTM C1260, the Kinetic Method, a modified Chinese Accelerated Mortar Bar Test, and real-time field exposure to evaluate the aggregates. They found that all of the sampled aggregates were determined to be reactive with the accelerated mortar bar tests. However, these tests are known for being overly conservative, and several of the aggregate sources were found to be only moderately reactive or non-reactive using ASTM C1293. Additionally, WYDOT has recently sponsored a project focused on evaluating treatment options for ASR-affected concrete [18], and is currently sponsoring a project focused on developing an accelerated test method using an autoclave to evaluate ASR potential in concrete that is more reliable than ASTM C1260 [19].

3.6 Federal Highway Administration

The Federal Highway Administration (FHWA) does not require any specific testing for ASR, but rather leaves it to the individual state departments of transportation to establish their own testing/mitigation protocols. However, the FHWA either directly or indirectly sponsors most of the research conducted on ASR. Further, the FHWA maintains a website with a large compilation of ASR research references, and helpful resources (https://www.fhwa.dot.gov/pavement/concrete/asr.cfm).

3.7 Federal Aviation Administration

The Federal Aviation Administration (FAA) directly addresses ASR in their material specifications for the construction of airports [20]. These specifications require that (within 6 months of the project) both fine and coarse concrete aggregates be tested in accordance with both ASTM C1260 and ASTM C1567, with an extended duration of 28 days. If lithium nitrate is to be used, the aggregates shall be tested in accordance with Corps of Engineers (COE) Concrete Research Division (CRD) C662 in lieu of ASTM C1567. In order to be deemed acceptable for use, the recorded expansions for a particular mix at 28 days must be less than 0.10%. If not, the mix must be modified and tested again.

In addition to these fairly stringent specifications, the FAA has also published a handbook to assist in identifying, preventing, and mitigating ASR in existing portland cement concrete pavements [21]. Specifically, this handbook provides a step-by-step procedure on how to identify ASR damage based on field inspection and laboratory investigation, and provides guidance in determining reaction severity and appropriate mitigation techniques. This handbook also discusses the use of an ASR condition survey, in which the FAA collects data on documented ASR cases; this data includes aggregate source, mix design, life, average rainfall, etc. The methodology presented within this handbook will be particularly useful during Task 3 of the overall research project, which is focused on identifying ASR damage in the state of Montana.

4 Aggregate Testing Methods

This section provides a brief summary of ASR-related testing methods, including both accepted and experimental tests for detecting reactive aggregates, and test methods for determining if damage in existing structures is associated with ASR.

4.1 Aggregate Testing Methods used in Practice

This section discusses the methods for testing for reactive aggregates that are currently used in practice.

4.1.1 Accelerated Mortar Bar Method - ASTM C1260/C1567 – AASHTO T303

The accelerated mortar bar test (AMBT) was first developed in the 1986 by Oberholster and Davies [22]. After some review and minor procedural changes, the AMBT method was adopted by ASTM in 1994 (ASTM C1260) and is currently the most widely used method for detecting reactive aggregates. ASTM C1567 is very similar to ASTM C1260, but is focused on determining the reactivity of mixtures containing combinations of cementitious materials and aggregates, rather than on just the cement and aggregates. Both of these tests involve immersing mortar bars in an alkaline solution at 80°C (176°F) for 14 days and monitoring their expansion. While these procedures provide rapid and repeatable results, they expose the aggregates to a fairly harsh environment (with an unlimited supply of alkalis and elevated temperatures) and have been known to be overly conservative when compared to results from other testing procedures (e.g., ASTM C1293) and when compared to field performance. Further, this test method does not allow for the testing of course aggregates at their standard size; that is, the course aggregates must be crushed and sieved to produce a sand with suitable size and gradation for the mortar bars.

4.1.2 Concrete Prism Test - ASTM C1293

The concrete prism test (CPT) was adopted by ASTM in 1995 (ASTM C1293), following its initial development as a Canadian test method [2]. This test method is known to be one of the more reliable test methods available for testing the reactivity of aggregates; however, its extended timeframe (1-2 years) limits its use in industry. This test procedure consists of casting concrete prisms with an increased alkali content, and then exposing these prisms to high humidity and elevated temperatures for 1-2 years. The expansion of these prisms is then monitored systematically over the duration of the test. This method has been shown to have better agreement with field performance than ASTM C1260, most likely due to its less harsh/more realistic exposure conditions, and the limited supply of alkalis. That being said, it has been known to produce false positive results [2]. Additionally, it should be noted that this test methodology allows for the testing of coarse aggregates in their standard size due to the larger 75-mm by 75-mm cross-section.

4.1.3 Petrographic Evaluation – ASTM C295

Concrete aggregates can be examined for potential reactive constituents using petrographic techniques. This petrographic examination should identify and quantify alkali-silica reactive constituents within the aggregates, such as opal, chalcedony, cristobalite, tridymite, highly strained quartz, microcrystalline quartz, cryptocrystalline quartz, volcanic glass, and synthetic siliceous glass. Based on the findings, additional tests may be recommended to confirm these findings.

4.1.4 ASTM C1778/AASHTO R80

Both ASTM and AASHTO recently released similar standards for determining the reactivity of concrete aggregates (in regards to both ASR and alkali-carbonate reactivity, ACR) and selecting appropriate mitigations measures: ASTM C1778 [23] and AASHTO R80 [24]. These standards do not introduce new testing procedures, but rather they provide guidance on how to test for reactive aggregates using existing methodologies (i.e., petrographic examination, accelerated mortar bar tests and concrete prism tests). They also provide guidance on and how to interpret test results and take appropriate measures, which include accepting an aggregate for use, avoiding using an aggregate, and/or mitigating reactivity. Mitigation methods for ASR can be selected using either a prescriptive or performance-based methodology, and since the potential for deleterious reactions depend both the concrete mix design and the in-service exposure of the concrete, guidance is provided based on the type of structure and the exposure environment. The mitigation methods include limiting the alkali loading of the concrete, using supplementary cementitious materials, using lithium admixtures, or a combination of these methods. The flow chart provided in Figure 3 [23] summarizes the procedure introduced in these standards. It should also be noted, that both of these standards state that if there is a proven history of satisfactory field performance then the aggregate source may be accepted for use with no precautionary measures. Regarding this, the standards also provide guidance for conducting a field survey of existing structures that were constructed using the same or similar aggregates, and that were exposed to similar conditions as the structure to be constructed.

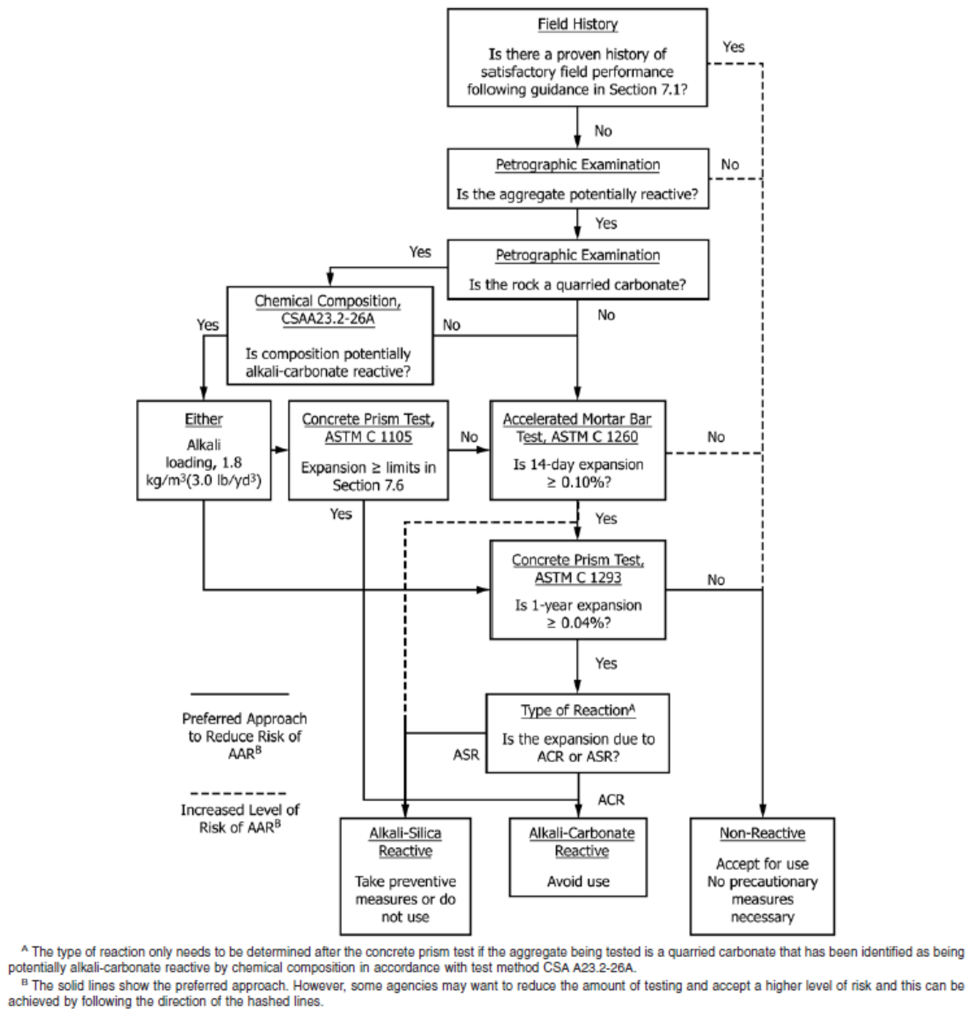

Figure 3: ASTM C1778/AASHTO R80 Flow Chart [23]

4.2 Newly Developed Aggregate Testing Methods

Several efforts are underway to develop aggregate testing methods that are more reliable than ASTM C1260, but are shorter in duration than ASTM C1293. The following subsections briefly discuss these methodologies.

4.2.1 Miniature Concrete Prism Test – AASHTO T380

The most promising aggregate testing methodology under development is the Miniature Concrete Prism Test (MCPT). This methodology is based off of research conducted by Latifee and Rangaraju [25] in 2014, and was recently adopted by AASHTO in 2018 [26]. This testing methodology is a hybrid between ASTM C1260 and ASTM C1293, using a similar testing procedure to ASTM C1260 with the mix design specified by ASTM C1293. The test specimens for the MCPT (cross-section dimension of 50 mm) are slightly larger than those used in ASTM C1260 (25 mm) and slightly smaller than those used in ASTM C1293 (75 mm). This size allows for the testing of coarse aggregates without the need for crushing, sieving, and combining. Regarding duration, the MCPT can characterize aggregate reactivity in 56 days, which is longer than the 14 days used in ASTM C1260, but significantly shorter than the 1 year required for ASTM C1293. It should also be noted that this test methodology can be used to test the potential for supplementary cementitious materials and admixtures to mitigate ASR expansions.

Although this methodology is fairly new and takes significantly less time to conduct, it has been shown to have good correlation with ASTM C1293 (the most reliable method) test results and field performance. In the original research conducted by Latifee and Rangaraju [25], aggregates with known field performance were tested with the MCPT methodology, and results were then compared to the results obtained from ASTM C1260 and ASTM C1293. The 56-day expansions recorded from the MCPT correlated well with the 365-day expansions recorded from ASTM C1293, with an R^2 value of 99% (Figure 4). It should also be noted that the Idaho Transportation Department is currently funding a research project focused on evaluating the advantages associated with implementing the MCPT within their specifications to quantify the ASR potential of aggregate sources in Idaho [11]. This project is scheduled to be completed in December 2019.

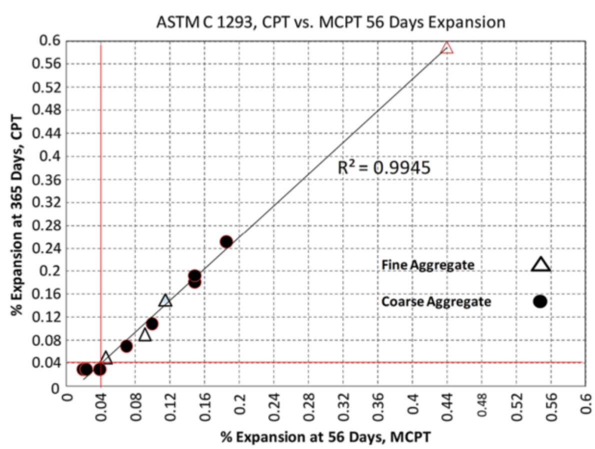

Figure 4: Correlation Between ASTM C1293 and MCPT Expansions [25]

4.2.2 Chinese Accelerated Mortar Bar Test

The Chinese Accelerated Mortar Bar Test (CAMBT) method is a combination of the Chinese Autoclave Method [27] and the standard accelerated mortar bar method. While this procedure has been shown to have good correlation with the accelerated mortar bar method, correlations with the CPT have been shown to be very poor [28], indicating that further research is necessary to establish the full reliability of the test. Similar to the shortcomings of the accelerated mortar bar method, the poor correlation may stem from the unrealistic and harsh testing environment that the specimens are exposed to.

4.2.3 Rapid Chemical Method for Determining Alkali-Silica Reactivity

Mukhopadhyay [29] proposed using a volumetric change measuring device to detect the amount of volume change due to ASR. The proposed method takes 5 days to complete instead of the standard 14-day AMBT testing procedure. The procedure involves placing aggregates in test chambers, heating them to specific temperatures in the presence of different alkalinity solutions, and measuring the changes in the pressures. This will yield activation energy and a threshold alkalinity level, which will allow for aggregate reactivity level as well as a recommendation for mitigation procedures outlined in the report. Tied to the Rapid Chemical Method, a kinetic-based classification system has been investigated using the data from the test [30]. The classification was effective in identifying aggregates as reactive and non-reactive which ASTM C1260 had false positive and negative results. This method demonstrates potential to be used as an alternative to ASTM C1260. However, more testing is required to establish its efficacy.

4.2.4 Autoclave Tests for Determining Potential Alkali-Silica Reactivity of Concrete Aggregates

The U.S. Army Engineer Research and Development Center (ERDC) recently developed a test methodology that is very similar to the ASTM C1260, where an autoclave is used to accelerate reactions: the Five-Hour Autoclave Test [31]. In this methodology, mortar bars of the same dimensions and mix proportions to ASTM C1260 specimens are cured for 48 hours before autoclaving at 130 ℃ for 5 hours, at which time expansions are observed. The researchers found that this test methodology obtained similar results to ASTM C1260 in 85% of the 20 samples tested, and agreed with results from ASTM 1293 in 100% of the 10 samples tested. However, further research is required to establish this test methodology as a viable alternative to standard ASR testing methods.

Similarly, a test method has been developed that uses an autoclave to accelerate reactions in ASTM C1293 concrete prisms [32]. During its development this testing methodology was shown to correlate well with ASTM C1293 and ASTM C1260 test results, and was shown to be superior to ASTM C1260 with regards to speed and accuracy. An ongoing research project at the University of Wyoming is focused on further developing and evaluating this testing methodology [19].

5 Methods for Identifying and Quantifying ASR Damage in Existing Concrete

The following sections discuss the methods available for identifying and quantifying ASR damage in existing concrete.

5.1 Los Alamos Staining Method

The Los Alamos Staining method [33] can be used to determine the presence of ASR in hardened concrete. This test involves placing various chemicals on the surface of fractured concrete, and depending the nature of the chemicals present, the chemicals will change color. This method provides a simple means for evaluating the extent and distribution of the gel products associated with ASR, and is easy to interpret (even for those not experienced in petrographic analysis). However, more accurate/thorough testing methods, such as petrographic analysis should be performed to fully characterize the damaged concrete.

5.2 Petrographic Analysis

The most accurate way of determining the presence and extent of ASR in hardened concrete is petrographic analysis. Some of the common petrographic techniques are listed below.

- Comprehensive petrographic analysis per ASTM C856, which examines a polished slab that represents the full length of a core that has been extracted from the site. This test examines air entrainment, determines depth of potential carbonation, characterizes cracks/microcracks, identifies rock types that are commonly susceptible to ASR, and identifies secondary deposits such as ASR gel and ettringite, which is commonly abundant in concrete with ASR.
- Scanning electron microscopy (SEM) with energy-dispersive x-ray spectrometry (EDS) per ASTM C1723. Along with higher magnifications, this test allows for in-situ chemical analyses of materials in a microstructure, and this test can positively identify if ASR gel is present.
- Damage Rating Index (DRI) analysis. This analysis inventories indicators of ASR in the concrete cores by subdividing cores into 25 x 25 mm (1 x 1 in.) cells and tabulating the number of various features that are associated with ASR (examples include reaction rims, debonded aggregates, deposits of gel in voids, deposits of gel in microcracks, etc.). This provides a method to compare levels of deterioration between different cores.

5.3 Non-Destructive Methods for Determining Damage Caused by ASR in Concrete

The U.S. Department of Energy Office of Nuclear Energy's Light Water Reactor Sustainability (LWRS) Program, aimed at extending the life of nuclear power plants, conducted research on non-destructive evaluation (NDE) methods for testing for the presence of ASR damage [34]. In their research, they used ultrasound to evaluate concrete slabs with varying levels of ASR. They found that the same technique developed for testing and quantifying freeze-thaw damage in concrete, the Hilbert Transform Indicator (HTI), may also be successful in testing ASR damage. This research determined that, while these two types of testing both correlate to damage in concrete in some ways, they do not allow for the finding of the depth or distribution of the cracks/damage.

Another group of researchers from various universities around the country conducted similar research on ultrasonic NDE techniques to evaluate damage in concrete resulting from ASR [35]. This study used three parameters of the ultrasonic testing as an attempt to measure ASR damage in concrete: wave speed, attenuation, and the amplitude of waves. The study found that wave speed and attenuation had poor correlation to ASR damage because of a lack of sensitivity. The amplitude of waves was more accurately used to quantitatively track ASR damage in concrete, and this parameter correlated well with the reduction of compressive strength resulting from ASR.

In another study, acoustic emission (AE) was used to test for ASR damage in concrete specimens [36]. AE is the release of stress waves produced from a sudden release of energy, such as cracking or expansion of concrete. Using highly sensitive sensors, internal cracks in concrete can be detected before they become visible. In this research, the activity from AE correlated well to the rate of expansion observed for concrete specimens expanding due to ASR, and correlated well to petrographic analysis.

6 SUMMARY

This literature review summarized ASR practices used by neighboring state departments of transportation, as well as several federal agencies. It was found that most regional states (Washington, Idaho, Wyoming, and South Dakota) directly address ASR in their material specifications, to varying degrees. The only regional state, of those investigated, that did not address ASR in their specifications was North Dakota. Regarding federal practices, the FHWA leaves it to the individual states to determine ASR practices, while FAA was found to have fairly stringent specifications.

Regarding aggregate testing methods, existing methodologies were discussed along with their shortcomings. ASTM C1260 is the most used methodology, but has been shown to have poor correlation to field performance. ASTM C1293 is the most accurate method, but is not used as often due to its prolonged duration (1-2 years). Several new testing methodologies are currently under development to overcome the shortcomings of these existing methodologies. The most promising of which is the miniature concrete prism test, which has recently been adopted by AASHTO as an aggregate testing methodology. This methodology was shown to have good correlation with ASTM C1293, but only takes 56 days to complete.

It should be noted, that as this research progresses this literature review will be continually updated. In particular, the regional practices will be expanded to include Canadian provinces and several other states.

7 References

1. Stanton, T.E., *Expansion of Concrete Through Reaction Between Cement and Aggregates*, in *Proceedings of the American Society of Civil Engineers*. 1940. p. 1781-1811.

2. Folliard, K., Fournier, B., Ideker, J., Shehata, M., and Thomas, M., *Test Methods for Evaluatin Preventaitve Measures for Controlling Expansion Due to Alkali-Silica Reaction in Concrete.* Cement and Concrete Research, 2006. **36**(10): p. 1842-1856.

3. Shrimer, F.H., *Progress in the Evaluation of Alkali-Aggregate Reaction in Concrete Construction in the Pacific Northwest, United States and Canada*. 2005, U.S. Geological Survey.

4. Lawler, J.S. and P.D. Krauss, *Development of High-Performance Concrete Mixtures for Durable Bridge Decks in Montana Using Locally Available Materials*. 2005, Montana Department of Transportation.

5. Stark, D., B. Morgan, and P. Okamoto, *Eliminating or Minimizing Alkali-Silica Reactivity.* Strategic Highway Research Program, 1993.

6. Gillerman, V., Weppner, K., *Lithologic Characterization of Active ITD Aggregate Sources and Implications for Aggregate Quality*. 2014, Idaho Transportation Department.

7. Fertig, R., et al., *ASR Potential and Mitigation Measures for Wyoming Aggregates.* Journal of Materials in Civil Engineering, 2017. **29**(9).

8. WSDOT. *Washington State Aggregate Source Approval Database*. 2019; Available from: https://www.wsdot.wa.gov/Business/MaterialsLab/ASA.htm.

9. WSDOT, *Standard Specifications for Road, Bridge, and Municipal Construction*. 2016, Washington Department of Transportation.

10. ITD, *2018 Standard Specifications for Highway Construction*. 2018, Idaho Transportation Department

11. Mishra, D. and E. Kassem, *Active Research: Implementing AASHTO TP 110 for Alkali-Silica Reaction Potential Evaluation of Idaho Aggregates*. 2019, Idaho Transportation Department.

12. NDDOT, *Standard Specifications for Road and Bridge Construction*. 2014, North Dakota Department of Transportation.

13. Hurcomb, D.R., K.F. Von Fay, and D. Albright, *Freezing and Thawing and Alkali-Aggregate Reaction Weakens Lightweight, Structural Concrete in North Dakota.* Cement Concrete and Aggregates, 2004. **26**(1): p. 9-13.

14. Buck, A.D., *Alkali Silica Reaction in Concrete in a North Dakota Highway*. 1984.

15. SDDOT, *Standard Specifiations for Roads and Bridges*. 2015, South Dakota Department of Transportation.

16. Johnston, D., *Lithium Field Implementation Trial*. 2007, South Dakota Department of Transportation.

17. WYDOT, *Standard Specifications for Road and Bridge Construction*. 2010, Wyoming Department of Transportation.

18. Basham, K., *Evaluation of Treatment Options for ASR-Affected Concrete*, in *Final Report*. 2009, Wyoming Department of Transportation.

19. WYDOT, *Ongoing Research Project: Development of an Ultra-Accelerated Test to Evaluate ASR Potential in Concrete*. 2016, Wyoming Department of Transportation.

20. FAA, *Standards for Specifying Construction of Airports*. 2018, Federal Aviation Administration.

21. FAA, *Handbook for Identification of Alkali-Silica Reactivity in Airfield Pavements*. 2009, Federal Aviation Administration.

22. Oberholster, R.E. and G. Davies, *An Accelerated Method for Testing the Potential Alkali Reactivity of Siliceous Aggregates.* Cement and Concrete Research, 1986. **16**(2): p. 181-189.

23. ASTM, *ASTM C1778 - Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete*. 2016, American Society for Testing and Materials.

24. AASHTO, *AASHTO R80 - Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*. 2017, American Association of State Highway and Transportation Officials.

25. Latifee, E.R. and P.R. Rangaraju *Miniature Concrete Prism Test: Rapid Test Method for Evaluating Alkali-Silica Reactivity of Aggregates*. Journal of Materials in Civil Engineering, 2015. **27**, 10 DOI: 10.1061/(asce)mt.1943-5533.0001183.

26. AASHTO, *AASHTO T 380 - Standard Method of Test for Potential Alkali Reactivity of Aggregates and Effectiveness of ASR Mitigation Measures (Miniature Concrete Prism Test, MCPT)*. 2018, American Association of State Highway and Transportation Officials.

27. Tang, M.S., S.F. Han, and S.H. Zhen, *A Rapid Method for Identification of Alkali Reactivity of Aggregate.* Cement and Concrete Research, 1983. **13**(3): p. 417-422.

28. Lu, D.Y., B. Fournier, and P.E. Grattan-Bellew, *Evaluation of Accelerated Test Methods for Determining Alkali-Silica Reactivity of Concrete Aggregates.* Cement & Concrete Composites, 2006. **28**(6): p. 546-554.

29. Mukhopadhyay, A., Liu, Kai-Wei, *Rapid Chemical Method for Determination Of Aggregate Alkali Silica Reactivity*. 2014, FAA.

30. Liu, K.W. and A.K. Mukhopadhyay, *A Kinetic-Based Asr Aggregate Classification System.* Construction and Building Materials, 2014. **68**: p. 525-534.

31. Wood, S.G., et al., *Five-Hour Autoclave Test for Determining Potential Alkali-Silica Reactivity of Concrete Aggregates: A Multi-Laboratory Study.* Advances in Civil Engineering Materials, 2017. **6**(1).

32. Giannini, E. and K. Folliard, *A Rapid Test to Determine Alkali-Silica Reactivity of Aggregates Using Autoclaved Concrete Prisms*. 2013, Portland Cement Association

33. Guthrie Jr, G.D. and J.W. Carey, *A Simple Environmentally Friendly, and Chemically Specific Method for the Identification and Evaluation of the Alkali-Silica Reaction.* Cement and Concrete Research, 1997. **27**(9): p. 1407-1417.

34. Clayton, D., L. Khazanovich, and L. Salles, *Linear Array Ultrasonic Test Results from Alkali-Silica Reaction (ASR) Specimens.* Oak Ridge National Laboratory, 2016.

35. Ju, T., et al., *Ultrasonic Nondestructive Evaluation of Alkali–Silica Reaction Damage in Concrete Prism Samples.* 2016. **50**(1): p. 60.

36. Abdelrahman, M., et al., *Classification of Alkali–Silica Reaction Damage Using Acoustic Emission: A Proof-Of-Concept Study.* Construction and Building Materials, 2015. **95**: p. 406-413.