

Development of an Ultra-Accelerated Test to Evaluate ASR Potential in Concrete

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Executive Summary

ASR is a global concrete durability problem with a complexity that continues to plague Wyoming. Although a simple, expeditious way to identify reactive aggregate, cement, and an appropriate mitigation measure does not exist; recent research shows promise of a week-long test to evaluate combinations of coarse and fine aggregates. This proposed test has the potential to replace the year-long concrete prism test.

Alkali silica reaction (ASR) is a significant problem in Cheyenne and other towns because of the presence of reactive aggregates. Although an effective mitigation technique exists in the form of adding effective fly ashes to concrete mix designs, not all fly ashes mitigate ASR in an equal manner. WYDOT's only means of evaluating fly ash as a mitigating agent is utilizing ASTM C1567 along with the history of the fly ash and the aggregates. The autoclave test would be extended to consider results of fly ashes combined with local aggregates. The overall goal is to provide a single test that can combine aggregates, cement, and mitigating measures within a one week time frame. Currently WYDOT ships fly ash from Texas to use as a mitigating. Finding locally available sources will improve sustainability and use a waste product.

If suitable fly ash is not available, WYDOT specifies that contractors add lithium nitrate to concrete design mixtures. The cost of this mitigation can be significant. The primary goal of this project is cost savings by producing durable concrete with an extended service life.

Problem Statement and Background

Alkali-silica reaction (ASR) is a global concrete durability problem, and the reactivity of certain aggregates has plagued the concrete around the world. Alkali-silica reaction (ASR) was first recognized as a distinct concrete durability problem in California in 1940 by Stanton who recognized that the reaction was dependent on the interaction of several factors including the type of cement, the aggregate used in the concrete mixture, and the environmental exposure conditions. Common reactive mineral types were found to include: opal, chalcedony, cristobalite, tridymite, and cryptocrystalline quartz (Hobbs 1988). More recent work identifies four ingredients that must be present in the concrete: reactive aggregate, sufficient alkali, calcium hydroxide, and sufficient moisture (Rajabipour et al. 2015; Thomas 2007). Alkali hydroxides in the concrete pore solution react with free silica in the aggregate, producing an alkali-silica gel product. This gel readily absorbs water and expands; this can lead to cracking and premature deterioration in concrete. The cyclic nature of the problem is illustrated in Figure 1 and examples are prevalent around the state as shown in Figure 2 and Figure 3. Sections of the highway with large pop-outs are inherently unsafe and should be fixed using simple and cost-effective measures.

The most widely accepted tests for evaluating ASR potential are the Accelerated Mortar Bar Test (AMBT or ASTM C1260) and the Concrete Prism Test (CPT or ASTM C1293). Each of these test methods are explained in detail in the following sections.

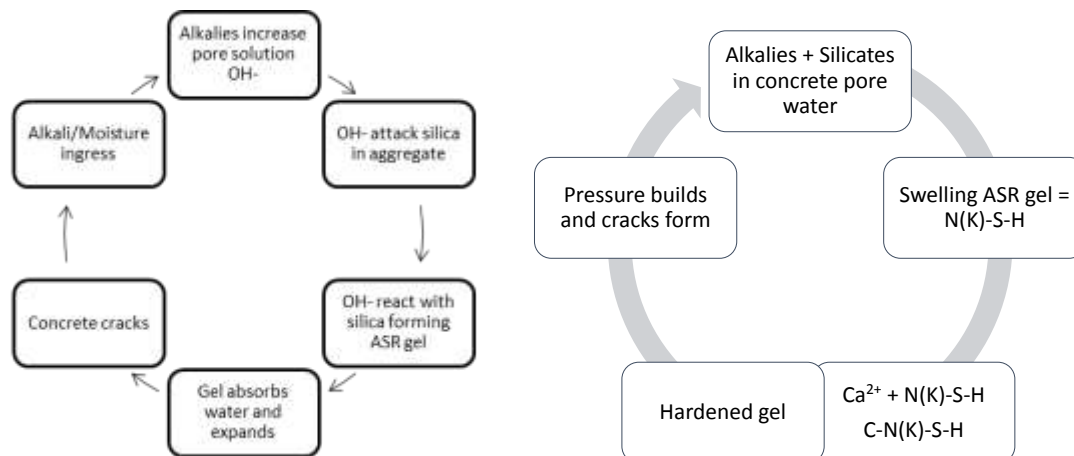


Figure 1. Cyclic nature of ASR in concrete. Chemical breakdown of types of gel.

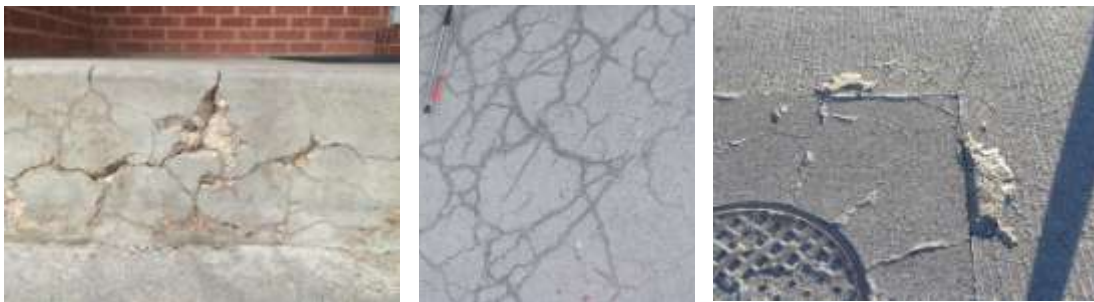


Figure 2. Examples of damage due to ASR in Wyoming a) concrete steps in Cheyenne, b) Federal Street in Riverton, and c) Federal and Pershing in Riverton

Mortar bar test

In 1986, Oberholster and Davies developed a test in South Africa (Oberholster and Davies 1986) that would eventually result in the ASTM C1260 test, formally adopted in 1994. The mortar bars are stored in 1 N NaOH solution at 80°C to accelerate the reaction, and the water/cement ratio is specified at 0.47. After casting, the bars are stored in a moist curing room for 24 hours. Then an initial comparator reading is taken, after which the bars are immersed in tap water at 80°C for 24 hours. The mortar bars are then placed in the NaOH solution at 80°C and measured periodically over the next 14 days. According to ASTM C1260, 14 day expansions less than 0.1% indicate an innocuous aggregate. Expansions greater than 0.2% indicate a highly reactive aggregate, and expansions between 0.1% and 0.2% mean the aggregate is potentially reactive. Some problems with ASTM C1260 test include false positives and false negatives. In some cases ASR reactions are not determined using this test method. (Sommer et al. 2000; Folliard et al. 2006) In other cases due to the harshness of this test, aggregates that would perform well in the field are discarded (Grattan-Bellew 2000; Lu 2000).



Figure 3. ASR damage on Interstate 80, east of Cheyenne a) general ASR map cracking, b) pop-outs combined with map cracking, and c) concrete failure between dowel bar retrofits is attributed to ASR.

Concrete prism test (CPT)

The development of the concrete prism test (CPT) began in the 1950s and was motivated by the failure of ASTM C227 to correctly identify both ASR and alkali-carbonate reactivity (ACR) (Thomas et al. 2006). The test uses 3 x 3 x 11 ¼” prisms with a w/c ratio between 0.42 and 0.45, a specific proportion of coarse and fine aggregate, and a cement content of 420 kg/m³. The cement should have a total alkali content the cement is boosted by the addition of NaOH to the mixture to yield a total alkali content of 1.25% by mass of the cement. An initial length measurement is then taken and the prism is placed in a 100% RH environment at 100°F (38°C). Unfortunately, this testing requires two years to evaluate a potential aggregate/fly ash combination because of the possibility of slowly reacting gel.

This test considers both fine and coarse aggregate combinations at the same time, rather than only one fraction as is done in mortar bar testing. Of the accelerated test methods, ASTM C1293 provides the best correlation with field performance and is therefore regarded as the most authoritative accelerated test for reactivity (Cornell 2002). The disadvantage to this test is that when evaluating the effectiveness of fly ash, the duration is two years because of the possibility of slowly reacting ASR aggregates.

Concrete prism tests are preferable to accelerated mortar bar tests for the following reasons:

1. it combines actual coarse and fine aggregates rather than crushing coarse aggregate into fine aggregate particle sizes;
2. it supplies a more realistic level of alkalis are provided rather than the unlimited source of alkalis used in the AMBT;
3. it is subjected to 100% relative humidity rather than being submerged in solution; and
4. it is run at 100 F which is closer to summer temperatures in Wyoming rather than 140 F.

Ultra-rapid concrete prism test (UR-CPT)

Recent work at the Universities of Alabama and Wyoming has provided insight into testing concrete prisms using an autoclave method to accelerate aging in prisms. Good agreement between the studies is an indication of the promise of this particular test method. The same concrete prisms used in the CPT test are placed in an autoclave at a temperature of 271 F. This method retains the advantages of the CPT test and reduces the duration considerably. A summary of testing details are highlighted in Table 1.

Table 1. Summary of test methods presented above.

Test Method	Advantages	Disadvantages
Mortar bar test	-Short duration -Relatively simple procedure	-False positives and negatives -High standard deviations between laboratories
Concrete prism test	-Combines coarse and fine aggregate -Simple procedure	-1 or 2 year duration
Ultra-rapid prism test	-Potential to eliminate the difficulties that plague mortar bar testing -Relatively inexpensive	-Under development -Limited data is available

Aggregate reactivity in Central and Southern Wyoming

The original project was funded to answer the question of how reactive are the aggregates in the big horn basin. There is a concern that unnecessary and expensive mitigation may occur due to false positives from ASTM C1567 in the Big Horn Basin. Eight Wyoming aggregate sources were selected for in-depth study of the ASR potential. After extensive testing, the UW research team provided a graphical classification illustrated in Figure 4 with results tabulated in Table 2. Reactivity is indicated by the size and color of the stars. For example, non-reactive pits are identified with a green star. Clearly Harris and Devries Farm pits, represented by green stars, do not need mitigation and this has reduced mitigation costs for WYDOT.

Field specimens were constructed as a method to provide real time performance and data will be collected at appropriate intervals based on the age of specimens. At the start of the project, the UW outdoor laboratory was one of five in the world and now 25 field exposure sites exist (Warner and Ideker 2012).

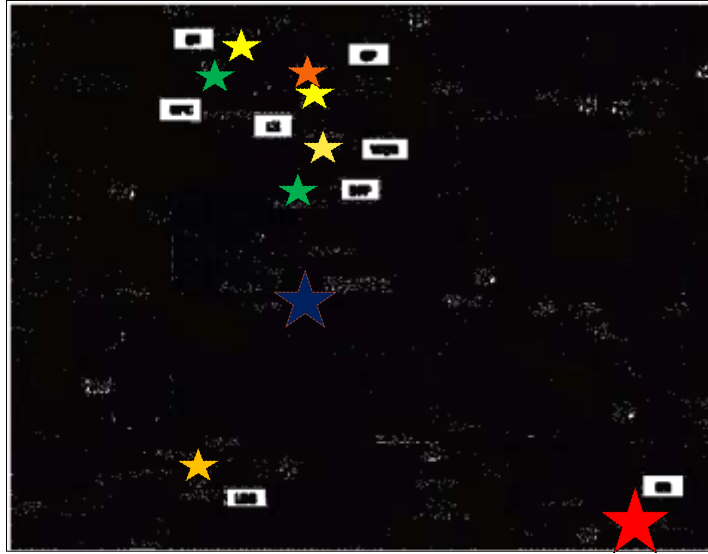


Figure 4. Location of aggregate sources in Wyoming. Reactivity is indicated by colored stars.

Table 2. Aggregate abbreviations and locations

Aggregate Name	Abbreviation	WY Location	Classification
Black Rock	BR	Powell	MR
Devries Farm	DFP	Thermopolis	NR
Goton	GP	Greybull	MR/HR
Harris	HP	Cody	NR
Knife River	KR	Cheyenne	HR
Labarge	LBG	Worland	MR
Lamax	LX	Basin	MR
Worland	WOR	Worland	MR

*NR=non-reactive, MR=moderately reactive, HR=highly reactive.

Ultra-accelerated autoclaved concrete prism test method

The proposed testing in this research accelerates concrete prism exposure time period by combining moderate pressures and temperatures. Specimens are created, initially cured, and then stored in an autoclave. This accelerated exposure provides results that could be available within one week. Figure 5 illustrates the results of four aggregates and 1293 results (Giannini and Folliard 2013). The correlation is very good.

Research on using autoclaving techniques is limited to those using the mortar bar tests (Grattan-Bellew 1997; Duchesne and Berube 1992; Fournier et al. 1991). As a result the disadvantages of the mortar bar test also apply to those research efforts. Extending the test method to evaluate prisms that combine coarse and fine aggregates makes the test specimens more realistic and other investigators show promising results (Giannini and Folliard 2013; Lui 2010; Lu et al. 2006)

Repeatability of any test method is necessary if this test method is to be considered on a larger scale. After additional work, Wyoming and Alabama have tested the same aggregates and

obtained similar results for two sources of aggregates, as shown in Figure 6. That data indicates promise of an ultra-accelerated test method to avoid the year-long delay in exposure time.

Preliminary results warrant evaluating and testing a larger number of aggregates. In addition, results could be compared to outdoor exposure blocks that are approaching 8 years old. Also, repeating the test procedure to combine coarse and fine aggregates fractions would match the WYDOT specification. This constitutes Phase I of the proposed research plan.

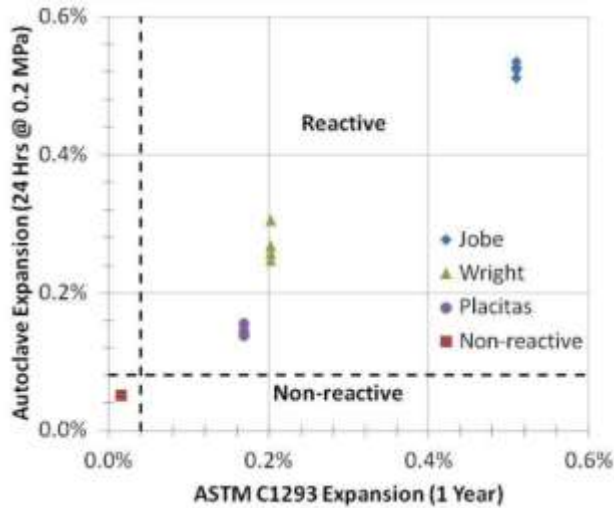


Figure 5. Preliminary results to compare CPT and autoclave test.

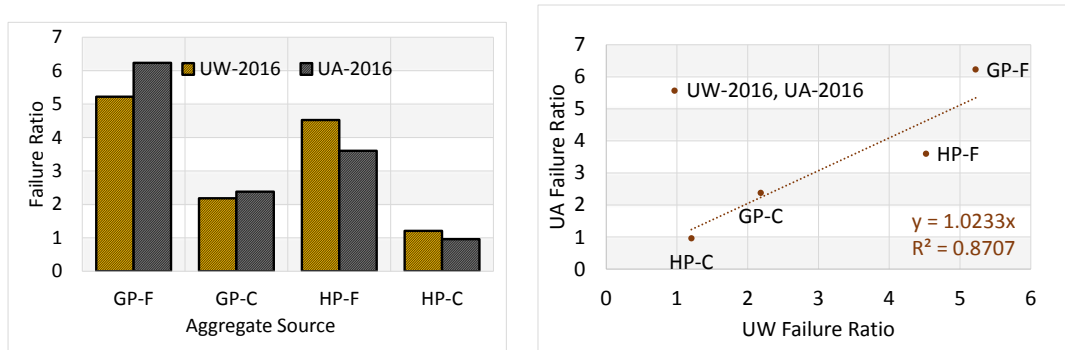


Figure 6. Repeatability measurements between UW and UA in a) bar graph and b) scatter plot.

Phase II of this proposal considers the chemistry of fly-ashes that are available to Wyoming. The quality and characteristics of fly ash vary widely based on the source of coal from which it is produced. Coals from bituminous sources are generally lower in CaO than those produced from subbituminous coals (Portland Cement Association 2002). A separate suite of tests to evaluate the effectiveness of fly ash mitigation using the 2-year CPT test will become available in August 2017. This research project will also pair the fly ash combinations with selected aggregates to determine the suitability of the autoclave test with fly ash.

This mitigation technique is sustainable because it uses a waste product to solve a current issue with concrete produced in Wyoming. Furthermore, it reduces the need to use a costly mitigating agent such as lithium.

Determination of frost action on field block specimens

Phase III of this project will collect data at month intervals during the course of a year to isolate if field block expansions are being exacerbated by freeze-thaw actions. Measured expansions for Knife River aggregates in Texas and Wyoming are compared in Figure 7. As expected, exposure blocks from the University of Texas expand more quickly. What is interesting to note is that the Wyoming field block expansions catch up to those in Texas and in the case of boosted specimens, they exceed those in Texas despite the colder climate in Wyoming. Measurements will be taken at a more frequent interval to determine if they grow more quickly in winter months.

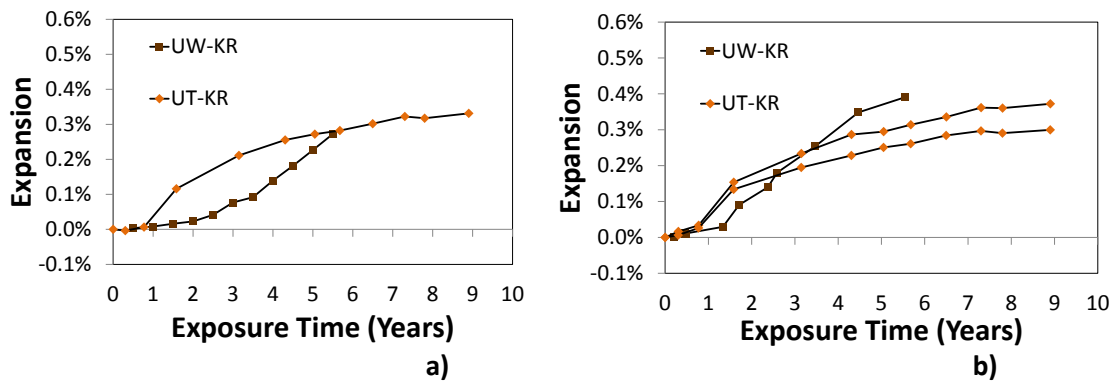


Figure 7. Comparison of average UW to UT field exposure expansion for KR - a) unboosted (UBFS) and b) boosted (BFS).

Additional studies on Recycled Concrete Aggregates

Previous research at Wyoming and Oregon State shows that recycled concrete aggregate (RCA) can be used to create durable concrete in new construction (Ideker, Tanner et al. 2012a, 2014). When heavily damaged ASR concrete is removed from the field, it can be mixed with virgin aggregates to create non-expansive, strong, and durable concrete. Wyoming has completed a round robin study of accelerated mortar bar tests (AMBTs) using recycled concrete aggregates among eight laboratories. As expected, the standard deviation was higher by combining recycled concrete aggregates with virgin aggregates.

A similar round robin study is proposed using the concrete prism test method. Although the duration is one-year, the anticipated benefits outweigh the time frame. Matching funds will be requested from the mountain plains consortium for this portion of the grant. In the event that matching funds are not awarded, this fourth phase will be eliminated from the project. This portion of the project adds sustainability to construction projects.

Project Summary

The overall project consists of four phases as described below.

Phase I – Evaluation of autoclave test using combined coarse and fine aggregates to compare results of unmitigated combinations of the CPT.

- Task 1 – Secure, prepare, and cast specimens.
- Task 2 – Measure and synthesize results.
- Task 3 – Work with WYDOT to confirm autoclave procedure.
- Task 4 – Perform validation test results to confirm results are within a given set.

Phase II – Additional ultra-rapid concrete prism testing that could permit WYDOT to evaluate source specific fly ash sources.

- Task 1 – Secure aggregates, prepare raw materials, cast specimens.
- Task 2 – Measure and synthesize results.
- Task 3 – Compare results to ongoing CPT specimens.

Phase III – Evaluation of frost action on field specimens.

- Task 1 - Measure field specimen expansions during winter and summer months.
- Task 2 – Compare and evaluate results.

Phase IV – Determination of effectiveness of RCA in CPT testing and further validation using the ultra-rapid concrete prism test.

- Task 1 – Collect RCA samples and prepare materials to ship.
- Task 2 – Perform testing of concrete prisms.
- Task 3 – Collect data from other laboratories.
- Task 4 – Synthesize and comment on variability of test results.

Work Schedule

This work would be completed by a PhD student with help from an MS student. A schedule for the entire project duration is presented in Table 3.

Table 3. Proposed schedule for project

Year	2017		2018				2019				2020		
Phase / Quarter	3	4	1	2	3	4	1	2	3	4	1	2	3
P1-T1	■	■	■	■									
P1-T2					■	■							
P2-T1				■	■	■							
P2-T2							■	■	■				
P3-T1	■	■	■	■	■	■	■	■	■	■			
P3-T2											■		
P4-T1	■	■											
P4-T2		■	■	■	■	■	■	■	■	■			
P4-T3											■		
P4-T4												■	■

Budget

The combined resources of WYDOT equipment available at UW create a project that builds on previous work at UW and elsewhere. The UW portion of the proposal requested from RAC is \$142.9K. A detailed budget is provided in Table 4. With matching funds from MPC the total project cost is 192.9K.

Table 4. Overall budget

Senior Personnel	Notes	UW request	WYDOT budget	MPC request
Tanner	2 months of support	\$ 12,014		\$ 7,208
Other Personnel				
PhD student	Three years of support	\$ 78,375		\$ 15,675
Undergraduate assistant	(\$10/hour x 10 hours/week x 12 weeks)*9%	\$ 654		\$ 654
Fringe Benefits				
Senior personnel x 49.863%		\$ 5,990		\$ 3,594
Operating Expenses				
Materials and supplies	Supplies for creating and testing specimens	\$ 5,000		\$ 2,500
Shipping	Shipping aggregate, cement and fly ash	\$ 2,500		\$ 1,500
Technical support	Machine shop time - 18 hours at \$50 per hour	\$ 600		\$ 300
Communications	Report publication/printing/editing	\$ 600		\$ 600
Laboratory fees	Equipment maintenance and upgrading autoclaves	\$ 2,000		\$ 550
Sample collection			\$ 10,000	
Travel				
Professional travel	Trips to present findings at professional meetings	\$ 3,000		\$ 2,000
Subtotal		\$110,733	\$ 10,000	\$ 34,582
Indirect Costs				
Direct costs x percentage	20% of costs WYDOT and 44.5% for MPC	\$ 22,147	-	\$ 15,389
Total RAC request	WYDOT contribution	\$142,880		\$ 49,970
Total project cost		\$192,850		

Salary is included for 5 semesters of PhD work as well as tuition and fees. The PI is funded for 1.25 months on this grant and 0.75 months on the MPC grant. Shop support is provided at 12 hours at a nominal rate of \$50 per hour.

Operating expenses include supplies and materials perform testing are included at 5K. Shipping aggregate or transporting to other laboratories is estimated at \$2.5K. Upgrading and maintaining laboratory space is 2.55K. Finally, a nominal budget of 0.6K is allotted for communications. The university overhead rate on the WYDOT portion of this project is 20%.

References

- ASTM C1260, *Standard Test Method for Potential Alkali Reactivity of Aggregates*
- ASTM C1293, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction*
- ASTM C1567, *Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)*
- ASTM C289, *Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates*
- ASTM C33, *Standard Specifications for Concrete Aggregates*

State-of-the-Art Report on Alkali-Aggregate Reactivity (2008) ACI 221.1

Cornell, B. D. (2002). Laboratory investigations of alkali silica reaction using the concrete prism test and its modifications. Austin, Texas, University of Texas at Austin.

Duchesne, J., & Bérubé, M. A. (1992, July). An autoclave mortar bar test for assessing the effectiveness of mineral admixtures in suppressing expansion due to AAR. In Proc. 9th Int. Conf. on Alkali-Aggregate Reaction in Concrete (Vol. 1, pp. 279-286).

Fertig, R., Tanner, J., (2012) "Evaluation of ASR potential in Wyoming aggregates using multiple accelerated tests" ICCAR 14th International Conference on Alkali Aggregate Reaction, May, Austin, TX.

Fiore, B., Tanner J., "Risk of Alkali-Silica Reaction when Using Recycled Concrete Aggregate in New Concrete" Final Report, Mountain Plains Consortium, December 2015, pp 60.

Folliard, K.J. et al. (2006). "Preventing ASR/DEF damage in new concrete." TxDOT Final Report 4085.

Fournier, B., Bergeron, G., & Bérubé, M. A. (1991). A rapid autoclave mortar bar method to determine the potential alkali-silica reactivity of St. Lawrence lowlands carbonate aggregates (Quebec, Canada). *Cement, concrete and aggregates*, 13(1), 58-71.

Fournier, B. and Berube, M. A. (2000). "Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications." *Canadian Journal of Civil Engineering* 27(2): 167-191.

Fournier, B., Nkinamubanzi, P.-C., Lu, D., Thomas, M. D. A., Folliard, K. J. and Ideker, J. H. (2006). Evaluating potential alkali-reactivity of concrete aggregates, how reliable are the current and new test methods. Marc-Andre Berube Symposium on Alkali-Aggregate Reactivity in Concrete, CANMET, Ottawa.

Grattan-Bellew, P. E., Lu, D., Fournier, B. and Mitchell, L. (2004). Mass Change, Petrography and Damage Ratings of Bars at the Completion of the Concrete Microbar Test. 12th International Conference on Alkali-Aggregate Reaction in Concrete, Beijing, China.

Grattan-Bellew, P. E. (1997). A critical review of ultra-accelerated tests for alkali-silica reactivity. *Cement and Concrete Composites*, 19(5), 403-414.

Giannini, E. R., Folliard, K. J., (2013) "A rapid test to determine alkali-silica reactivity of aggregates using autoclaved concrete prisms." Portland Cement Association, SN 3235, Skokie, Illinois, USA, pp 21.

Hooton, R. D. and Rogers, C. A. (1993). "Development of the NBRI rapid mortar bar test leading to its use in North America." *Construction and Building Materials* 7(3): 145-148.

Ideker, Jason. (2012), "Do Current Laboratory Test Methods Accurately Predict Alkali-Silica Reactivity?," *ACI Materials Journal*, Title no. 109-M37, V. 109, No. 4 July-August.

Ideker J., Adams M., Tanner J., Jones A., (2012a) "Durability Assessment of Recycled Concrete Aggregates for use in New Concrete: Phase I" Oregon Transportation Research and Education Consortium (OTREC), OTREC RR-11-09, June 2012, pp 61.

Ideker J., Adams M., Tanner J., Jones A., (2014) "Durability Assessment of Recycled Concrete Aggregates for use in New Concrete: Phase II" Oregon Transportation Research and Education Consortium (OTREC), OTREC RR-13-01, July 2014, pp 98.

Ideker, J., Drimalas, T., Bentivegna, A., Folliard, K., Fournier, B., and Thomas, M. (2012b). "The Importance of Outdoor Exposure." 14th ICAAR. Austin, TX.

Kimble M., Fertig R., Hacker D., Tanner J., "Evaluation the Risk of Alkali-Silica Reaction in Wyoming: Continued Evaluation of Field Specimens and Proposed Mitigation Strategies" Final Report, Federal Highway Administration, Wyoming Department of Transportation, FHWA-WY-15/04F, September 2015, pp 191.

Kimble M., Fertig R., Jones A., Tanner J., "Evaluation of ASR Potential in Wyoming Aggregates" Final Report, Federal Highway Administration, Wyoming Department of Transportation, FHWA-WY-13/04F, October 2013, pp 156.

Kosmatka, S. H., Kerkhoff, B. and Panarese, W. (2002). *Design and Control of Concrete Mixtures*. Skokie, IL, Portland Cement Association.

Liu, C., Lee, C., Wang, W.C. (2011). "Study of autoclave methods for evaluating the alkali-silica reactivity of aggregates." *Journal of the Chinese Institute of Engineers*, 34(5), 663-670.

Lu, D., Fournier, B. and Grattan-Bellew, P. E. (2006). "Evaluation of accelerated test methods for determining alkali-silica reactivity of concrete aggregates." *Cement and Concrete Composites* 28(6): 546-554.

Lu, D., Mei, L., Xu, Z., Tang, M., & Fournier, B. (2006). "Alteration of alkali reactive aggregates autoclaved in different alkali solutions and application to alkali-aggregate reaction in concrete:(I) Alteration of alkali reactive aggregates in alkali solutions". *Cement and concrete research*, 36(6), 1176-1190.

Lu, D., Fournier, B., Grattan-Bellew, P. E., Xu, Z. and Tang, M. (2007). "Development of a universal accelerated test for alkali-silica and alkali-carbonate reactivity of concrete aggregates." *Materials and Structures* 41(2).

Lu, D., Fournier, B., Grattan-Bellew, P. E., Xu, Z. and Tang, M. (2008). "Development of a universal accelerated test for alkali-silica and alkali-carbonate reactivity of concrete aggregates." *Materials and Structures* 41(2).

Mielenz, R. C., Greene, K. T. and Benton, E. J. (1948). "Chemical Test for Reactivity of Aggregates with Cement Alkalies: Chemical Processes in Cement-Aggregate Reaction." *ACI Proceedings* 44: 193-219.

Oberholster, R. E. and Davies, G. (1986). "An accelerated method for testing the potential alkali reactivity of siliceous aggregates." *Cement and Concrete Research* 16(2): 181-189.

Portland Cement Association, PCA, (2002). "Supplementary Cementing Materials for Use in Concrete", Educational DVD.

Rear, K., Meinheit, D. F., Chrest, A. P., Brown, R., Breeze, P. C., Clarke, J. L. F., D'Arcy, T. J., Durning, T., Eddy, D. B., Gami, S. S., Iverson, P. J., Magnesio, C., Nadeau, F. A., Peterson, C. A., Schupack, M. and Walker, H. C. (1994). "Alkali-Aggregate Reactivity: A Summary." *PCI Journal* (Nov-Dec): 26-35.

Schumacher, K., Ideker, J.H. (2014). "New Considerations in Predicting Mitigation of Alkali-Silica Reaction Based on Fly Ash Chemistry." *J. of Materials in Civil Engineering*.
[http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0001021](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001021)

Sommer, H., Nixon, P. J. and Sims, I. (2005). "AAR-5: Rapid preliminary screening test for carbonate aggregates." *Materials and Structures* 38(8): 787-792.

Stanton, T. E. (1940). "Expansion of concrete through reaction between cement and aggregates." *Proceedings of the American Society of Civil Engineers* 66(10): 1781-1811.

Thomas, M., 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* 36(10): 1842-1856.

Warner, S., Ideker, J. (2012). "Alkali-silica reactivity and the role of alumina." ICCAR 14th International Conference on Alkali Aggregate Reaction, May, Austin, TX.