Evaluating the Effectiveness of Fly Ashes to Mitigate ASR and Using Recycled Concrete Aggregate in New Construction

WYDOT Sponsors

Chris Romo, P.E.
Principal Materials Engineer
5300 Bishop Boulevard
Cheyenne, WY 82009
Telephone: (307) 777-4074

Bob Rothwell, P.E.
Assistant State Materials Engineer
5300 Bishop Boulevard
Cheyenne, WY 82009
Telephone: (307) 777-4071

Greg Milburn, P.E.
State Materials Engineer
5300 Bishop Boulevard
Cheyenne, WY 82009
Telephone: (307) 777-4070
Principal Investigator

Jennifer Tanner, Ph.D.
Assistant Professor
Department of Civil and Architectural Engineering
University of Wyoming
Laramie, WY
Telephone: (307) 766-2073

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Programming Research Unit
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Cheyenne, WY 82009
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Executive Summary

ASR is a global concrete durability problem with a complexity that demands respect. Even though the fundamental constituents of the reaction were identified when ASR was first recognized; a complete understanding of the mechanisms of reaction remains elusive. A simple, expeditious way to identify reactive aggregate, cement and an appropriate mitigation measure does not exist. If concrete design mixtures are overly conservative, the state wastes valuable resources. Alkali silica reaction (ASR) is a significant problem in Cheyenne because of the presence of a known, highly reactive aggregate. Although an effective mitigation technique exists in the form of adding effective fly ashes to concrete mix designs, not all fly ashes mitigate ASR. Furthermore, the level of reactivity of an aggregate should be considered.

Recent work at the University of Wyoming indicates that aggregates located in the Big Horn Basin, Labarge, and Knife River (Cheyenne) can be mitigated by replacing 25% of the cement using fly ash from Craig, Colorado. In addition, it may be possible to use even less fly ash. Availability of ASR mitigating fly ashes is limited and this proposal considers other potential fly ash sources. For example, one particular fly ash that Wyoming contractors use is shipped to Wyoming from Texas. As resources become scarce it becomes important to have multiple sources of fly ash to mitigate our reactive aggregates. If fly ash is not available, WYDOT may need to specify that contractors add lithium to concrete design mixtures. This is a very expensive proposition. The primary goal of this project is cost savings by producing durable concrete with a long service life.

This work would pair Wyoming aggregates with alternate fly ash sources. Moderate to highly reactive aggregates would be evaluated based on four test methods. It is unfortunate that the most reliable test method, the concrete prism, requires two years to determine if a fly ash source is acceptable. This is compounded by that fact that not all fly ashes have the same chemical makeup. In this work, results of four complimentary tests would be performed to expand the number of mitigation options and use materials more readily available to Wyoming contractors. In particular, fly ash from more local sources will be considered and perhaps a fly ash from the four corners area. One of the four methods explores a new engineering methodology. Finally, using recycled concrete as a new source material in new concrete construction is proposed. The goal is to develop precision statements for using RCA in new concrete construction. This part of the project combined with using locally available fly ash has a positive impact on the environment and overall construction cost.

Problem Statement and Background

Alkali-silica reaction (ASR) was first recognized as a distinct concrete durability problem in California in 1940 (Stanton), and it has been identified in countries all over the world since then. Stanton 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. The reaction can be described by a two-step process. Alkali hydroxides in the concrete pore solution attack and react with the free silica in the aggregate to produce an alkali-silica gel reaction product. Then this gel absorbs water and expands which leads to the expansion and cracking of the concrete (Rear et al. 1994). Examples of ASR affected concrete are shown in Figure 1.

Soon after the problem was recognized, the need for an accelerated test to evaluate cement-aggregate combinations became apparent. In the 1950s, ASTM C227 was passed, calling for mortar bars stored at 100% relative humidity. Shortly afterwards, a chemical method was developed at the Bureau of Reclamation (Mielenz et al. 1948) and was first accepted as an ASTM standard in 1952. Similar to ASTM C227, ASTM C289 is not used as frequently anymore due to the development of the ASTM C1260 test and C1293 tests. A general description of each test is provided below and a summary of advantages and disadvantages are included in Table 1.

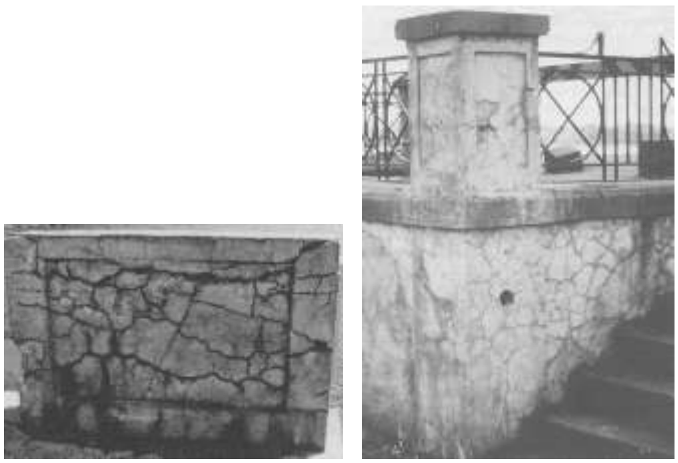

Figure 1. Examples of ASR in a beam (Bragg 2000) and a retaining wall (Shrimer 2000)

Table 1. Summary of test methods

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
Semi-accelerated prism test	-Data is available for US and Canada -Combines coarse and fine aggregate -Three month duration.	-Not standardized -Some outliers exist
Ultra-rapid prism test	-Potential to eliminate the difficulties that plague mortar bar testing -Relatively inexpensive	-Under development -Limited data is available

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).

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/m^3. 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.

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. Researchers continue to look for a test with the same accuracy that can also be completed in a shorter time frame.

Results of mortar bar testing versus concrete prism testing are shown in Figure 2. The scatter in these graphs shows some of the problems with the mortar bar test. Wyoming data shows an inverse trend between the two methods, or a negative correlation as shown in Figure 3.

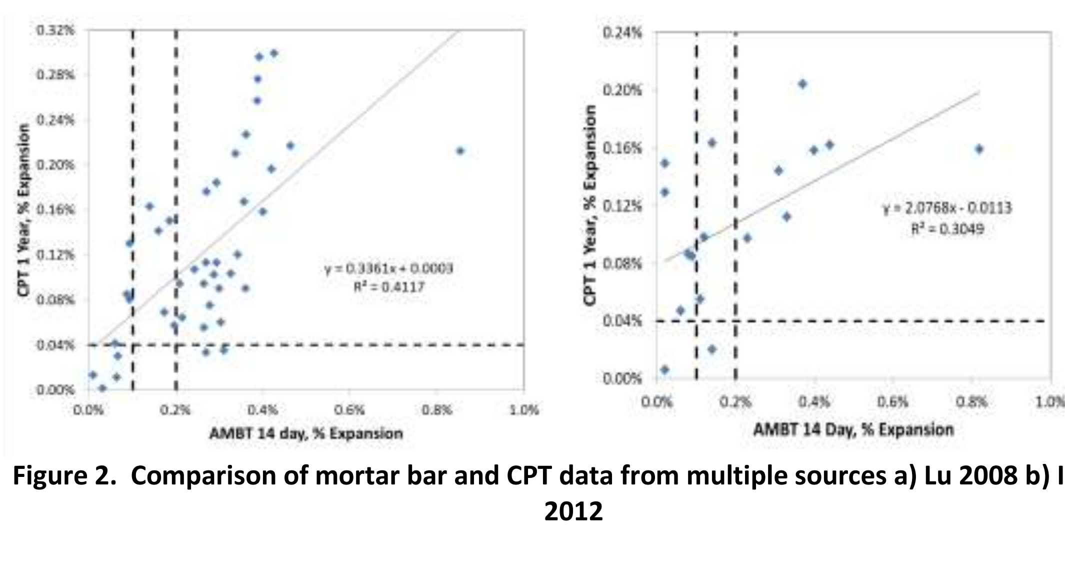

Figure 2. Comparison of mortar bar and CPT data from multiple sources a) Lu 2008 b) Ideker 2012

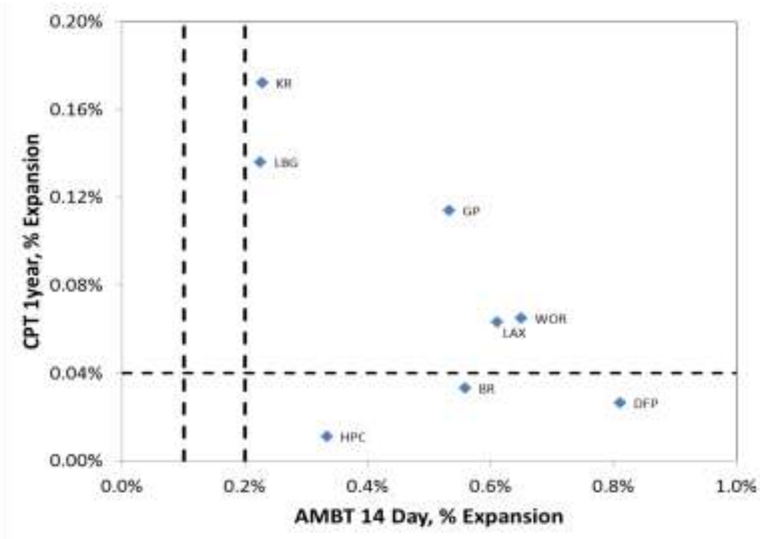

Figure 3. Inverse trend between mortar bar and CPT expansions for Wyoming aggregates

Accelerated concrete tests

Although the most respected ASR test is the concrete prism test, it is rarely conducted by departments of transportation because of the one or two year duration. Two alternative tests exist. The first is a three month test at 176°F (80°C). Other details are consistent with the CPT. Because concrete blocks are tested, coarse and fine aggregates are evaluated together and this is what occurs in the field. While there is general correlation between this and other ASR tests, some outliers exist and that is why this method has not been adopted by the American Society of Testing Materials (ASTM). This test will be performed as a baseline to expand the existing set of data on this semi-accelerated test.

An alternate ultra-accelerated test was developed by Giannini (University of Alabama) and Folliard (University of Texas). There is good correlation with a limited number of aggregates. In this test, a set of concrete prisms is cast and cured in an autoclave under low pressure and moderate temperature. Specimens are exposed for a short time and then tested. This method warrants further study because results would be available in a week. In addition, the cost is relatively low if an autoclave is available.

Mitigation measures using fly ash

The most cost-effective and common way to mitigate ASR is to replace a percentage of cement with fly ash. Expansions can be reduced by using a design mixture with low alkalis, Na_2O_e, and a low calcium oxide (CaO) content. Measured expansions from concrete blocks with various levels of total alkalies are shown on the left and a reduction in expansion using fly ash replacement is shown on the right side of Figure 4.

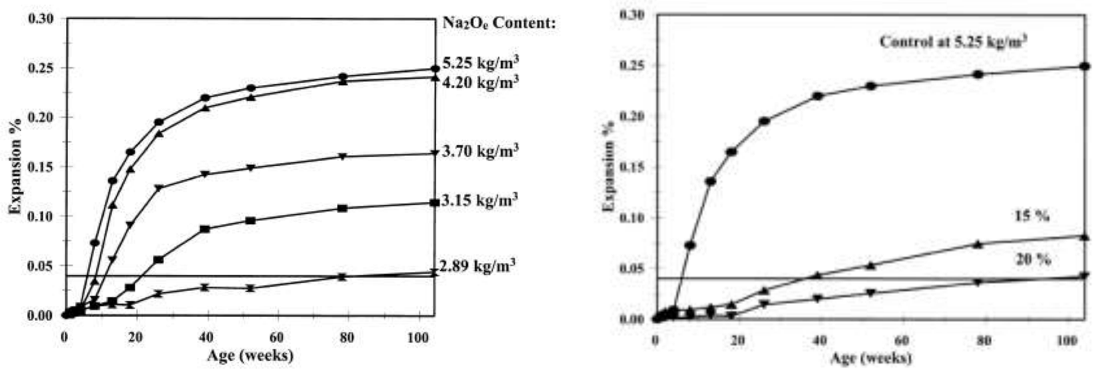

Figure 4. Measured expansions using various levels of total alkalies and fly ash replacement (Shehata 2000)

Another set of data illustrates the effect of using fly ash with various CaO contents, Figure 5. In this figure fly ash classifications are based on Canadian definitions. Type F has a CaO percentage less than 8 and expansions are below the limit of 0.04% for all three mixtures. Between 8 and 20% CaO, some concrete mixtures fall below the expansion limit. Yet in the same range, four groups clearly exceed the expansion limits as illustrated by the red oval. When CaO levels exceed 20%, very few of the concrete mixtures are mitigated. The situation is further compounded by the fact that fly ashes coming from subbituminous coal operations generally have higher levels of CaO (PCA 2002). A study to evaluate fly ash mixtures that indeed mitigate is important. If fly ash is not available, the next step is to add lithium to the concrete mixture which is very expensive. Furthermore, adding a high quality fly ash to moderately reactive aggregates is an overly conservative course of action.

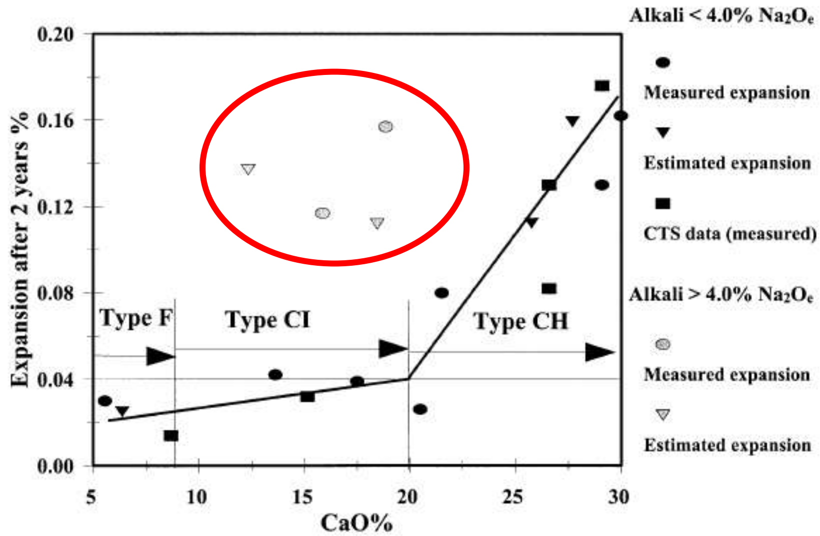

Figure 5. Effect of CaO level on expansion using a 25% fly ash replacement (Shehata 2000)

ASR knowledge for Wyoming aggregates and fly ash sources

Eight Wyoming aggregate sources were selected for in-depth study of the ASR potential and results are identified in Figure 6 and Table 2. Reactivity is indicated by the size and color of the stars. For example, non-reactive pits are identified with a green star. Field specimens were constructed as a method to provide real time performance and data will be collected through the year 2018. At the start of the project, the outdoor laboratory was one of five in the world and now 25 field exposure sites exist (Warner and Ideker 2012).

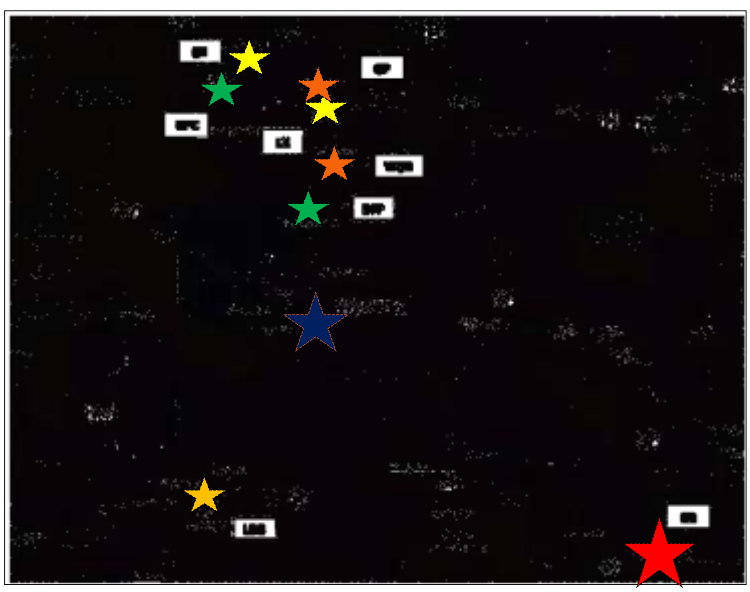

Figure 6. Location of aggregate sources in Wyoming. Reactivity is indicated by colored stars.

The original project was funded to answer the question of how reactive are the aggregates in the big horn basin. Now that pits are better classified, the question of how to handle moderately or reactive aggregates remains. Clearly Harris and Devries Farm pits do not need mitigation. Do Lamax and Labarge sources need to be treated with the same quality of fly ash as aggregates from Knife River? Guidance for this question can be found in the following paragraphs.

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	R
Harris	HP	Cody	NR
Knife River	KR	Cheyenne	VHR
Labarge	LBG	Worland	MR-R
Lamax	LX	Basin	MR
Worland	WOR	Worland	R

*NR=non-reactive, MR=moderately reactive, R=reactive, VHR=very highly reactive.

Kimble (2014) verified that fly ash from Craig, CO is effective in mitigating all of the aggregates shown above. In Figure 7a, expansion limits of standard concrete blocks are compared to concrete mitigated with Craig fly ash. The left vertical axis defines a failure ratio, or a generally accepted limit to classify aggregates as reactive. Anything above 1 indicates a potentially reactive aggregate. Blue bars represent unmitigated concrete and the red bars represent expansions when replacing 25% of the cement with fly ash. Data for mortar bar tests are shown in Figure 7b. Clearly all eight Wyoming aggregates can be mitigated based on this data. The more reliable CPT test data shows that a fly ash replacement level of 25% is very conservative for this particular fly ash because four out of the six aggregates had negligible expansions. If other sources are available to mitigate moderately reactive aggregates, this could be a way to conserve fly ashes that that work effectively with very highly reactive aggregates such as Knife River. Alternately, different fly ash sources could work to mitigate less reactive aggregates.

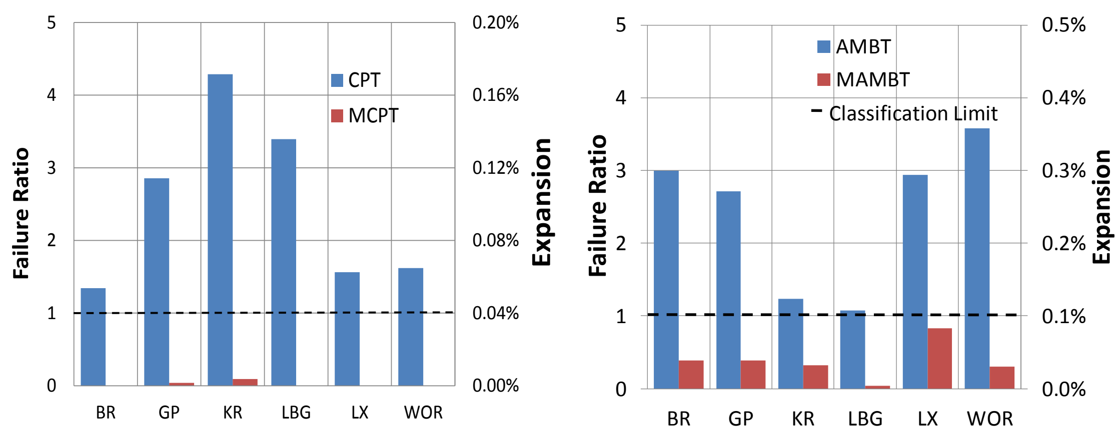

Figure 7. Comparison of original and mitigated data for a) concrete prisms and b) mortar bar tests

Another Wyoming fly ash, Bridger, is not as consistent as Craig fly ash for mitigating ASR. WYDOT has mixed results relating to the mitigating potential of the Bridger ash. Some data indicate successful mitigation while other data shows limited to no mitigation. One reason for this difference could be that Bridger fly ash is suitable to mitigate moderately reactive aggregates, but not very highly reactive aggregates such as Knife River. The testing program is aimed to answer this question. If more rapid tests are satisfactory for Wyoming materials, the state would experience a significant cost benefit by avoiding treating concrete with lithium. Another end result would be extending the service life of new concrete construction.

Chemical analysis of fly ash
Prior to performing a battery of tests on any particular fly ash, the research team will consider the chemical content of potential fly ash sources. Suppression of ASR requires a low ratio of CaO to SiO; the ratio of available ash is 0.18 which is well below the ratio of 0.8 for typical Class C fly ash (Mindness et al. 2003). Furthermore the aluminum oxides are 23.5%, which is greater than the recommended 20% (Warner and Ideker 2012). Schumaker and Ideker (2014) have proposed an analytical method to determine if fly ash is suitable for mitigation based on chemical composition. This technique will be applied to each potential fly ash. Finally, the research team will join forces with the WYDOT materials laboratory to select appropriate fly ashes based on history and availability for WYDOT construction projects. A guide will be developed and shared with the materials laboratory in the event they wish to test additional fly ashes in the future.

Semi-rapid prism test
Several researchers have performed testing on concrete prisms using a 3 month, test (Fournier 2004, Folliard et al. 2006). Although it is not as quick as the mortar bar tests, it is certainly better than a 2 year long test. Some of the major disadvantages of the mortar bar or concrete prism test are avoided. Furthermore, data is available from both Texas and Canada. The research team will gather, process, and compare all available results to determine if this is a suitable alternative for Wyoming. Also, we can compare these results to field specimens and the mitigated CPT data because both research groups have long-term data from field sites to expand the overall data set. One example of such a comparison is shown in Figure 8a and b. The left figure has two year CPT data on the horizontal axis and the right figure has field block expansions on the horizontal axis. After the research team combines all available data and creates plots similar to those shown below, the correlation will likely decrease. That said, if the trend does not differ, WYDOT could justify evaluating new fly ash sources in a shorter time frame. The reliability of mitigation techniques will improve, resulting in decreased maintenance costs during the service life of the concrete.

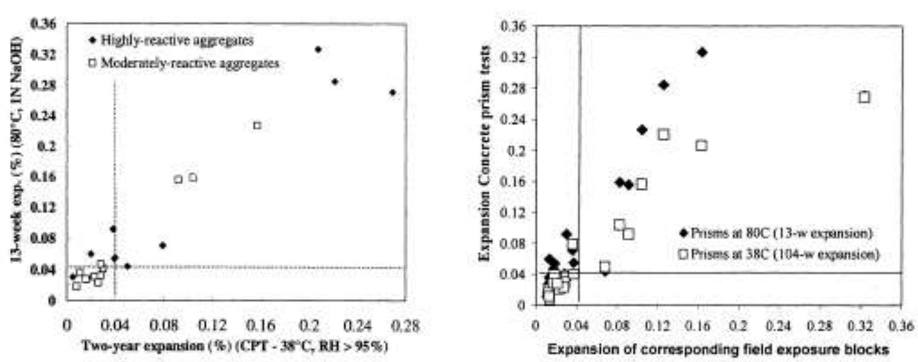

Figure 8. Comparison of semi-rapid test to a) CPT data and b) field block data for the original Canadian (CANMET) field block site (Fournier 2004).

Ultra-accelerated concrete prism test method

This test accelerates concrete prism exposure by combining pressure and temperature. Because specimens are stored and cured in autoclave, results could be available within one week. Figure 9a illustrates the results of four different aggregates and there is a very good correlation between this ultra-accelerated test and 1293 results (Giannini 2012). Wyoming and Alabama have tested the same aggregates and obtained similar results for fine aggregates, as shown in Figure 9b. This inexpensive technique should be evaluated using fly ash as a mitigating agent. As with the previous project, Alabama will complete companion specimens using fly ash. Repeatability of any test method is necessary if this test method is to be considered on a larger scale. Prior to confirming the validity of this test, a larger number of aggregates must be evaluated and compared to field results.

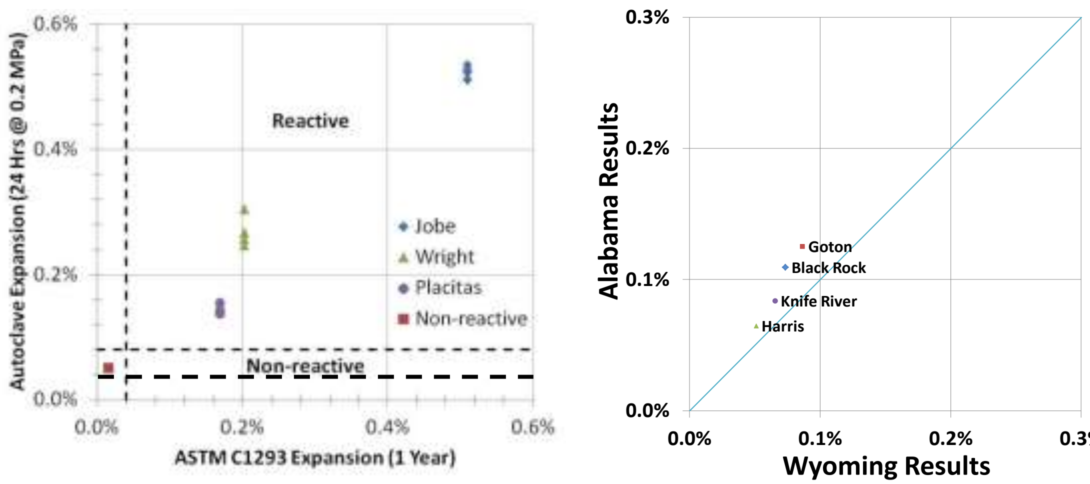

Figure 9. a) Preliminary results to compare CPT and autoclave test and b) comparison between UW and UA for autoclave testing of Wyoming fine aggregates.

Future sources of non-reactive aggregates

Recent 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. The theory behind this apparent contradiction is that the ASR reaction in RCA has run its course and is now non-reactive. For example, a concrete design mixture with 65% RCA was used on a section of Interstate 80 between Cheyenne and Pine Bluffs. The remaining 35% aggregate was non-reactive and fly ash was included in the design mixture. After 25-30 years, this stretch of pavement has limited ASR damage.

A separate project funded by the Mountain Plains Consortium (MPC) has found very reliable information that the hypothesis works for replacement levels of 20 to 50%. A round robin study of mortar bar tests among seven laboratories is underway. Field block specimens with six or more years of exposure provide an excellent source of RCA. Furthermore, the material properties are well known. Up to three field specimens would be crushed and processed to provide additional data points. One would be a boosted specimen and the other would be unboosted. The overall aim of the MPC project is to develop ASTM precision statements to use in mortar bar testing to evaluate reactivity of recycled concrete aggregates.

Project Description

The overall project consists of four parts and individual tasks within each phase. Phases include: continued monitoring of field specimens; evaluation of mitigation strategies; evaluation of the hypothesis that RCA can actually mitigate ASR; and further evaluation of moderate to reactive aggregates.

Phase I – Mortar bar and concrete prism tests of moderately and highly reactive aggregates

A series of tests will be conducted on a minimum of two fly ashes for Knife River, Labarge and one of the two reactive aggregates in the Big Horn Basin. This combination evaluates moderately reactive, reactive and very highly reactive aggregates. Oven space permits us to test two levels of fly ash for Labarge and the Big Horn Basin aggregate. UW will present a final testing program based on our aggregate inventory and available fly ash sources. Task 1 is the CPT and 2 is the mortar bar testing.

Phase II – Additional concrete prism testing that could permit WYDOT to evaluate specific fly ash sources

Both of the proposed accelerated prism test methods aim to reduce the duration of the standardized prism test without sacrificing accuracy. The more common 3 month test can be conducted at UW by retrofitting an existing oven within the Civil Engineering Department. This comprises Task 1. The more rapid autoclave testing would be Task 2.

Phase III – Testing recycled concrete aggregates

One group of field specimens has an extra three blocks. Once six year data is available, three could be demolished and used to make recycled concrete aggregate. The remaining three field specimens will still be measured with the entire group. Boosted specimens will provide highly reactive RCA and unboosted blocks will provide moderately reactive RCA. If just five other groups complete companion studies, additional data will become available to justify developing a standard for testing RCA that has been damaged by ASR. Data collection is Task 1 and analysis is Task 2.

Phase IV – Continued monitoring of field specimens

Field specimens will continue to be monitored as Task 1. The same instrumentation and technique will be employed to ensure that data collection remains constant. In addition, control specimens exist that can be used to account for global changes in thermal conditions or other anomalies that may be present over time, Task 2. Writing the final report will occur during the final two years and Task 4 is a period for the project managers to review and comment on the report.

Work Schedule

The proposed project occurs over a 42 month time frame. A graduate student for this project could begin working hourly in November 2014 and begin full time work as a graduate student in September 2015. Mr. Bryce Fiore has a 3.7 GPA and is certified as a concrete tester. A schedule for the entire project duration is presented in Table 3.

Table 3. Proposed schedule for project

Year	2015				2016				2017				2018		
Phase / Quarter	1	2	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 $66K between November 2014 and September 2018. A detailed budget is provided in Table 4. With matching funds from MPC the total project cost is 96K.

Table 4. Overall budget

Senior Personnel	Notes	UW request
Tanner	3 weeks of support	$ 7,038
Other Personnel		
MS student	Three semesters of support	$ 33,875
Undergraduate assistant	($10/hour x 10 hours/week x 10 weeks)*9%	$ 1,090
Fringe Benefits		
Senior personnel x 46.55%		$ 3,276
Operating Expenses		
Materials and supplies	Cement, curing containers and general supplies	$ 2,500
Shipping	Shipping aggregate, cement and fly ash	$ 2,000
Technical support	Machine shop time - 12 hours at $50 per hour	$ 600
Communications	Report publication/printing/editing	$ 600
Laboratory fees	Equipment use and maintenance	$ 1,500
Travel		
Professional travel	Trips to present findings at professional meetings	$ 2,500
Subtotal		$ 54,979
Indirect Costs		
Direct costs x percentage	20% of costs	$ 10,996
Total RAC request	WYDOT contribution	**$ 65,975**
MPC matching funds	Mountain Plains Consortium	$ 30,234
Total project cost		$ 96,209

Salary is included for 3 semesters of student work as well as tuition and fees. For the first 10 months of the project, the graduate student will be funded at an hourly rate of $10. During the final 16 months the traditional stipend plus tuition and fees is included in the budget. The PI is funded for 0.75 month. Shop support is provided at 12 hours.

Operating expenses include supplies and materials perform testing are included at 2.5K. Shipping aggregate or transporting it between UW and WYDOT is estimated at $2K. Upgrading and maintaining laboratory space is 2.7K. The university overhead rate on this project is 20%.

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ASTM C1293, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction*

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ASTM C289, *Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates*

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