Appendix A: Literature Review

Appendix A of *NCHRP Research Report 1083: Alkali-Silica Reactivity Potential and Mitigation: Test Methods and State of Practice* (NCHRP Project 10-103).

The National Cooperative Highway Research Program (NCHRP) is sponsored by the individual state departments of transportation of the American Association of State Highway and Transportation Officials. NCHRP is administered by the Transportation Research Board (TRB), part of the National Academies of Sciences, Engineering, and Medicine, under a cooperative agreement with the Federal Highway Administration (FHWA). Any opinions and conclusions expressed or implied in resulting research products are those of the individuals and organizations who performed the research and are not necessarily those of TRB; the National Academies of Sciences, Engineering, and Medicine; the FHWA; or NCHRP sponsors.

Contents

List of Figures

1.0 Introduction

The goal of this research project is to improve the Guidance of AASHTO R 80/ASTM C1778 for alkali-silica reactivity (ASR) potential and mitigation. Alkali-silica reaction is a subclass of the larger category of alkali aggregate reactivity (AAR), which includes both alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). This report and project only cover implications of ASR. From the project proposal the main aims to meet the goal include:

1. Construct and evaluate field exposure blocks with varying concrete materials placed in diverse environmental conditions to supplement the existing information.
2. Enable improved benchmarking of current performance and job mixture tests that have been developed or are being developed currently.

The recently developed AASHTO R 80-17 Practice (previously AASHTO PP65) and ASTM C1778-16 Guide have significantly improved the way the concrete industry assesses aggregates for potential alkali-aggregate reactivity (AAR) and, subsequently, guides selection on appropriate mitigation methods to use potentially alkali-silica reactive (ASR) aggregates in new concrete construction. These standard practices/guide documents were a result of several FHWA- and DOT-funded research projects focused on evaluating the potential for, and the prevention of, alkali-silica reaction (Folliard et al. 2006, Thomas et al. 2008, Thomas et al. 2012) and were also informed by the Canadian Standards Association (CSA) approach to ASR (CSA-A23.1, 2009). Two members of our team (Thomas and Fournier) were also involved with the development of the Canadian practice. A unique feature of these projects was the use of long-term outdoor exposure blocks to benchmark accelerated laboratory tests against concrete exposed to actual environmental conditions. At the time of developing these practices/guide documents and corollary reports, there was evidence of generally good correlation between accelerated laboratory tests (e.g. ASTM C1260/1567/1293) and the outdoor exposure blocks. The majority of the outdoor exposure blocks were made with mixture proportions matching ASTM C1293, with cementitious materials contents of 420 kg/m^3 (708 lb/yd^3) and high alkali cements (~0.8 to 1.25 Na_2O_{eq}), which resulted in an unusually high alkali loading. Continued questions arise regarding the representative nature of these blocks: *1) do they accurately predict field concrete and 2) shouldn't we know what happens in blocks with a broader and lower range of alkali loadings*? This is the driving force behind this research project and the need to validate or modify the recommendations in AASHTO R80 and C1778.

The data from over 1,000 long-term exposure blocks collectively located in Austin, Texas; Ottawa, Ontario, Canada; Fredericton, New Brunswick, Canada; Treat Island, Maine and most recently in Corvallis, Oregon have provided the most representative samples for bench-marking ASR in field concrete with accelerated laboratory tests. In the past five years we have learned that our previous confidence in the reliability of current test methods to predict the efficacy of mitigation options has come into question. As the concrete in the outdoor exposure sites has further matured, it has been revealed that a great many of the mitigated mixtures that passed current accelerated laboratory tests (ASTM C 1293 – concrete prism test and/or ASTM C1260/1567 – accelerated mortar bar tests), and thus should have high resistance to ASR, are now showing deleterious expansion from ASR in the outdoor exposure blocks after 7-20 years of exposure (depending on the site location, mixture specifics, etc.). This represents a disconnect between laboratory and field experience that merits further investigation to determine the root cause(s) and identify potential improvements to accelerated test methods, specifications, and guidelines. These findings question the reliability of the prescriptive approaches laid out in AASHTO R80 and ASTM C1778 and undermine the confidence in performance testing using accelerated laboratory tests to verify long-lasting pavements and highway infrastructure. Figure 1 shows data that demonstrate the disconnect between the ASTM C1293 two-year concrete prism test and 10-year-old field exposure blocks for a highly reactive (R3 according to C1778 classification) fine aggregate with a wide variety of mitigation options (e.g. binary and ternary blends of SCMs and/or lithium nitrate). The lack of correlation that has become evident within the past few years is a significant concern. Over 60% of these mixtures passed the ASTM C1293 two-year concrete prism test (<0.04%) but have shown deleterious expansion in the exposure blocks.

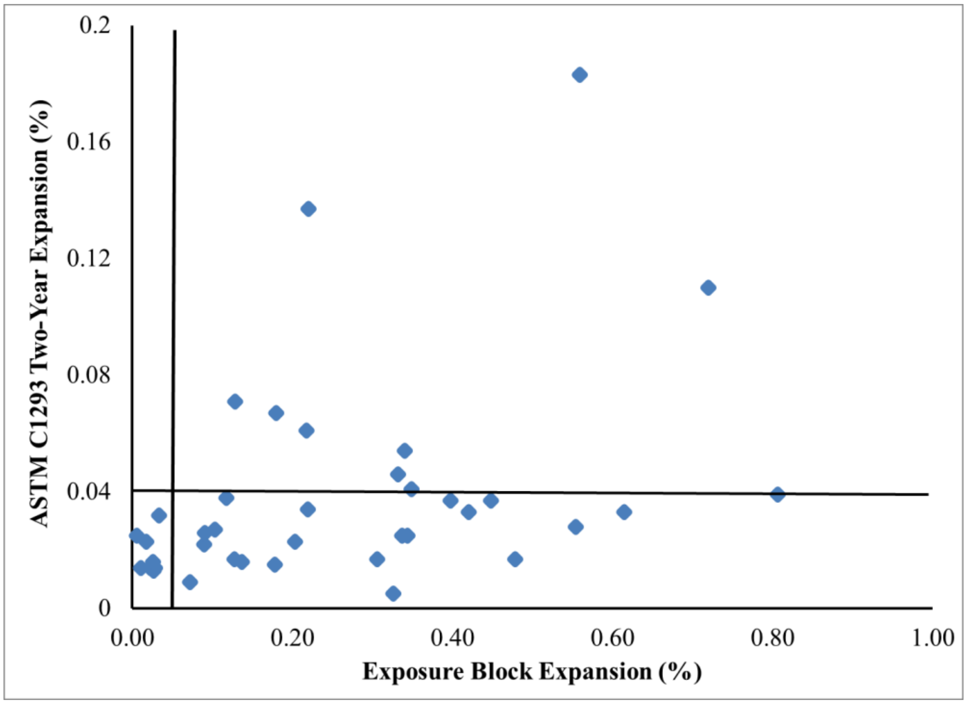


Figure 1. Exposure Blocks containing SCMs in Austin, TX showing the disconnect between ASTM C1293 to Exposure Blocks. Exposure block data is after 10 years on the Austin site.

One issue that arises from the results of the current outdoor exposure blocks is that they seem to be overly aggressive for evaluating ASR. The mixture design of the blocks does not represent concrete mixtures used in concrete pavement and most other highway infrastructure applications.

The blocks generally follow ASTM C 1293 for mixture proportions, with a high content (708 lb/yd^3) of high-alkali cement (0.90 +/- 0.10% Na_2O_{eq}) that is then "boosted" by adding NaOH to the mixing water to obtain a total alkali content of 1.25% Na_2O_{eq}. This approach yields a total alkali content of 5.25 kg/m^3 (8.85 lb/yd^3 Na_2O_{eq}) in the concrete, which may be as much as two to three times higher than the alkali contents in typical highway concrete mixtures. These sites also have blocks that are "unboosted," meaning they were cast using the same high-alkali cement, but without boosting with additional alkalies, resulting in ~0.90% Na_2O_{eq} or 3.78 kg/m^3 (6.37 lb/yd^3 Na_2O_{eq}) in the concrete. For each block cast, ASTM C 1293 testing was performed for two years. From our current inventory of exposure blocks, we now know that a reliable relationship between ASTM C1293 and outdoor exposure blocks does not exist for mixtures that contain SCMs or lithium.

1.1 Research Team

This research project will be completed by a team of experts from three universities (Dr. Thano Drimalas (PI) and Dr. Kevin Folliard (Co-PI) – The University of Texas at Austin, Dr. Jason H. Ideker (Co-PI) - Oregon State University and Dr. Michael D.A. Thomas (Co-PI) - University of New Brunswick) and one consultant (Benoit Fournier – Université Laval) along with their respective graduate research students. This team has the most extensive experience in North America and are all world-renowned experts related to researching the mechanisms underlying alkali-silica reaction, mitigation techniques, the development of test methods, establishing the linkage to field concrete and investigating ASR in full-scale structures and translating research and experience into standards and guidance documents.

2.0 Review of Existing Literature

2.1 Introduction to ASR and Current Problem

Two types of alkali-aggregate reaction (AAR) are generally recognized and these are:

Alkali-carbonate reaction (ACR):	which is defined as the reaction between the alkali hydroxides released by the Portland cement and certain types of argillaceous dolomitic limestones.
Alkali-silica reaction (ASR):	which is defined as the reaction between the alkali hydroxides and certain types of amorphous, cryptocrystalline or poorly-crystalline silica found in some aggregates.

Both reactions can result in expansion of the concrete and may eventually cause cracking. Although the chemical pathways of the two types of reaction are very different the symptoms of distress are very similar as shown in Figure 2.

ASR was first reported by Thomas Stanton almost 80 years ago when he identified the reaction as the cause of cracking in numerous structures in Monterrey County in California (Stanton, 1940). Some 20 years later, ACR was discovered by Ed Swenson as the cause of abnormal cracking in sidewalks, curbs, floors and foundation walls in Kingston, Ontario, Canada (Swenson, 1957). Occurrences of ASR have been reported all over the world and there are cases in all 48 contiguous states of the USA and all 10 provinces of Canada. Cases of ACR, on the other hand, are relatively few and occurrences have been restricted to only a few countries and 4 or 5 states in the USA. This literature review is only concerned with ASR as this the focus of the research study and proposed workplan.

Figure 2. Photograph of ASR in a concrete wall (left) and ACR in a concrete sidewalk (right)

A comprehensive review of both ASR and ACR, including details of reaction mechanisms, methods of testing and measures of prevention, was published earlier by the authors of this report (Thomas et al. 2013). A review of ASR in the USA and Canada, including a discussion of the geographic distribution of ASR cases and reactive aggregates, and specifications was also published by the authors (Thomas et al. 2017a)

2.1.1 Overview of the Reaction, Manifestations

Beyond the first day the pore solution of concrete is dominated by sodium (Na^+) and potassium (K^+) ions balanced by hydroxyl ions (OH^-) with the pH typically being in the range of 13.2 to 14.0. The source of the alkalis (sodium and potassium) is predominantly the Portland cement component of the concrete. Despite its name, alkali-silica reaction starts with the attack by the hydroxyl ions in the pore solution on certain forms of silica (SiO_2) in the aggregate. At high concentrations of OH^-, the silica dissolves and the negatively charged Si-O- ions attract positively charged sodium

(Na^+) and potassium (K^+); the reactions can be written as follows (modified from Dent Glasser and Kataoka, 1981a; 1981b):

$$\text{Si-OH} + \text{OH}^- + \text{Na}^+ \rightarrow \text{Si-O-Na} + \text{H}_2\text{O} \qquad \text{Equation 1}$$

$$\text{Si-O-Si} + 2\text{OH}^- + 2\text{Na}^+ \rightarrow 2(\text{Si-O-Na}) + \text{H}_2\text{O} \qquad \text{Equation 2}$$

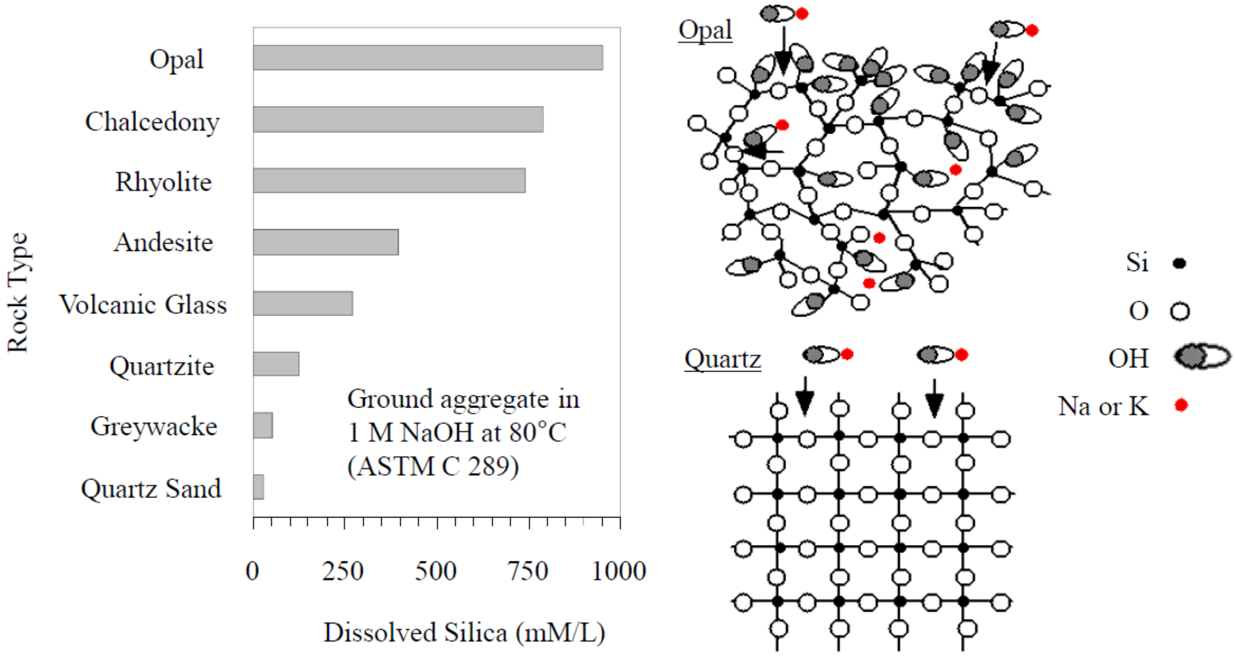
The initial product of the reaction is an alkali-silicate solution or gel depending on the moisture content; however, in the presence of calcium, the silica precipitates from solution as an alkali-silicate gel ($CaO\text{-}Na_2O/K_2O\text{-}SiO_2\text{-}H_2O$), primarily composed of sodium, potassium and silica, with small amounts of calcium. It should be noted that not all forms of silica are deleterious reactive; for example, well-crystallized quartz (SiO_2) will not react to any significant degree even at very high concentrations of alkali hydroxide. Although the precise mechanisms of expansion are equivocal, the production of the gel and its subsequent imbibition of water results in internal expansion within the concrete which may ultimately lead to cracking of the concrete as shown in Figure 2.

Other manifestations of distress include closing of expansion joints, misalignment of adjacent elements, localized crushing, popouts, and operational problems associated with embedded mechanical equipment. The expansion and cracking can lead to a loss in mechanical properties (strength and stiffness) and, although the structural integrity of the affected concrete may not be greatly affected, the cracking can significantly reduce the service life of concrete due to increased rates of deterioration from other processes such as chloride ingress and corrosion for reinforced concrete or freeze-thaw cycling in concrete pavements.

2.1.2 Aggregates, Reactivity Levels, etc.

The potential for an aggregate to cause deleterious alkali-silica reaction depends on a wide number of factors including the amount, type, distribution and habitat of the reactive silica present in the aggregate and the size of the aggregate. The following silica minerals are considered to be alkali-silica reactive: opal, tridymite, cristobalite, volcanic glass, chert, cryptocrystalline (or microcrystalline) quartz and strained quartz. These minerals may be found in the following rock types: shale, sandstone, silicified carbonate rocks, chert, flint, quartzite, quartz-arenite, gneiss, argillite, granite, greywacke, siltstone, arenite, arkose and hornfels. However, this does not mean that all sources of such rocks will produce deleterious reaction when used in concrete. For example, granitic aggregate is widely used in concrete and only certain sources produce damaging ASR. The reactivity of a rock depends on the type and quantity of reactive minerals present, if any.

Figure 3 shows the solubility of various minerals and rock types when immersed in a solution of 1 Molar NaOH at 80°C (176°F). Quartz and opal which are both predominantly composed of SiO_2 show very different behavior which can be explained on the basis of differences in crystalline structure of these two minerals. Opal has a highly disordered (amorphous) structure which renders it unstable at high pH and, as such, aggregates containing significant quantities of the mineral opal may be expected to react and result in expansion when used in concrete, provided there is sufficient alkali present. On the other hand, well-crystalline quartz will not react deleteriously regardless of the alkali content of the concrete.



(a) Soluble Silica in Aggregates

(b) Schematic Showing Crystalline Structure of Opal (top) and Quartz (bottom)

Figure 3. (a) Solubility of different forms of silica (Grattan-Bellew, 1989) and (b) differences in the structure of opal and quartz Dent Glasser and Kataoka, 1981)

Poorly crystalline or amorphous silica minerals such as opal, cristobalite, volcanic and artificial glasses react rapidly and may cause damaging reaction in a few years when present in amounts as little as 1%. Varieties of quartz such as cryptocrystalline, microcrystalline or strained quartz react more slowly, take longer to produce damage, and are generally required to be present in greater quantities than poorly crystalline and amorphous forms of silica. However, it is difficult to classify aggregate reactivity based solely on mineralogy as aggregates may contain various types of reactive minerals in different quantities, and the extent to which reactive minerals cause damage in concrete depends on other factors such as particle size.

Generally, the rate of expansion increases as the particle size of the reactive aggregate decreases; however, if the particle size is reduced to a very fine size expansion does not occur. In his formative work on ASR, Stanton (1940) showed that expansion did not occur when the reactive aggregate was ground to pass a 180-micron sieve (Figure 4a). Vivian (1951), using the same aggregate presented data to show that the particle size had to be reduced below 50-micron to eliminate expansion. It is now fairly well established that reactive silica ground to sufficient fineness can actually prevent ASR expansion when used with reactive aggregate as the finely-ground silica behaves like a pozzolan sequestering the alkalis in the pore solution thereby making them unavailable for reaction with the aggregates (Thomas, 2011). This is shown in Figure 5 which shows expansion data for mortar bars containing crushed (Vycor) glass as a reactive sand when stored over water at 38°C (100°F). Mortar bars from the control mix containing 100% Portland cement (PC) as the cementing material expanded rapidly as did mortar bars containing 80% PC diluted with 20% ground quartz. However, substitution of the PC with 20% ground (Vycor) glass, from the same source as the sand, effectively prevented deleterious expansion.

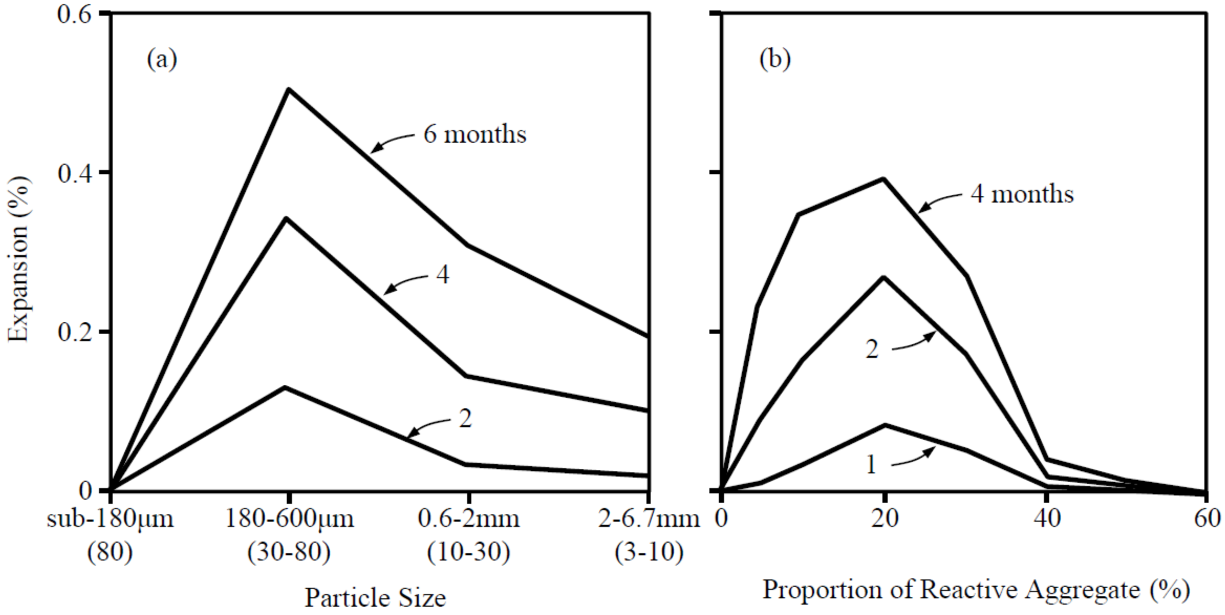


Figure 4. Effect of size (a) and proportion (b) of reactive aggregate (from Stanton, 1940)

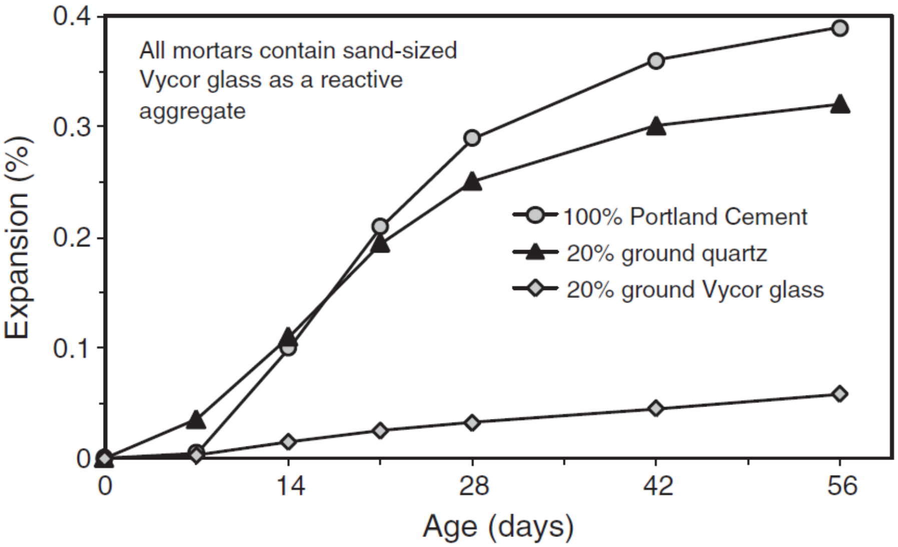


Figure 5. Effect of ground glass on the expansion of mortar containing crushed glass sand (Thomas, 2011)

Some reactive minerals exhibit a pessimum behavior in that the expansion does not necessarily keep increasing with the content of the reactive phase and the maximum expansion may occur at some intermediate reactive mineral contents. In such cases, very high contents of the reactive mineral may not produce any deleterious expansion. This is shown in Figure 4b from Stanton's (1940) paper where maximum expansion occurred when the proportion of reactive aggregate was 20% whereas little or no expansion occurred when the content of reactive aggregate was increased to 40 or 60%.

Usually petrographic examination will reveal the presence of potentially alkali-silica reactive minerals in an aggregate provided that the silica is not too finely disseminated through the matrix to make it "invisible" to optical microscopy techniques. However, because the potential for damaging reaction and expansion is dependent on many factors as discussed here, it is usually recommended that the potential for damage is determined using an appropriate expansion test using mortar or concrete containing the aggregate in question. Such tests are discussed below.

2.1.3 Cement Alkalinity, Alkali Loading

In the first major published paper on ASR, Stanton (1940) demonstrated experimentally and concluded the following:

> *"The chemical reaction producing excessive expansion apparently occurs only when the portland cement component contains an appreciable percentage of alkali in the form of sodium and potassium oxides. It is of an intensity proportional to the percentage of such oxides, apparently being of such low order as to be negligible when the alkali content is less than 0.6%."*

This defined the concept of "low-alkali cement" for almost 8 decades. Until recently, ASTM C150 Specification for Portland Cement had an optional requirement for low-alkali cement defined as cement with an equivalent alkali content of less than or equal to 0.6% Na_2Oe and a great many specifications worldwide adopted this requirement as an option to prevent deleterious ASR when reactive aggregates were used.

Whilst reducing the alkali content of the cement undoubtedly reduces the risk of damaging ASR it is now generally recognized that it is the total alkali burden of the concrete that is the controlling factor in Portland cement concrete that does not contain supplementary cementing materials (SCM). This is demonstrated in Figure 6 which shows the expansion of concrete produced with the same reactive aggregate (Spratt) and a wide range of cement contents and cement alkali levels. It is apparent from the data that the expansion is a function of the concrete alkali content which is calculated by multiplying the cement content of the concrete by the alkali content of the cement.

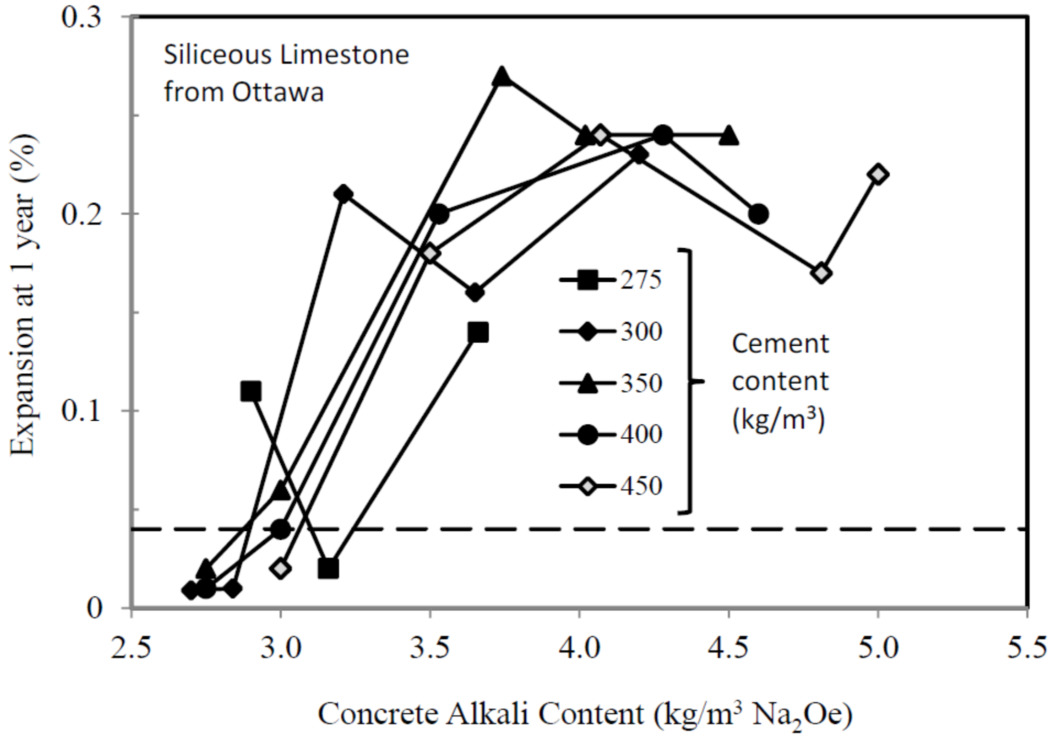


Figure 6. Relationship between the expansion of concrete prisms and the alkali content of the concrete (Portland-cement concretes only) from Thomas et al (2017b)

However, it must be noted that the alkali content required to produce expansion in laboratory tests where concrete specimens are stored over water in sealed containers is significantly greater than that required to produce expansion in larger specimens (exposure blocks) stored in field conditions. For example, the data shown in Figure 6 indicate that damaging expansion will not occur with this aggregate (Spratt) if the alkali content of the concrete is below 3.0 kg/m^3 (5.0 lb/yd^3) Na_2Oe. However, in field-exposure studies deleterious expansion has occurred when the alkali content of the concrete has been below 2.0 kg/m^3 (3.4 lb/yd^3) Na_2Oe (Hooton et al. 2013). This phenomenon is discussed in detail in other parts of the report.

In the recently published Canadian standard practice for preventing damaging ASR (CSA A23.2-27A, 2019) four different maximum alkali contents are given to provide increasing "Levels of Prevention" from W to Z as shown in Table 1. Similar levels of prevention are given in AASHTO R80-17 and ASTM C1778 -19 except that control of the alkali content is not permitted as the sole preventive measure for Prevention Level Z.

Table 1. Maximum Alkali Contents in CSA A23.2-27A, 2019

Prevention Level	Maximum Alkali Content (Na_2Oe)	
	kg/m^3	lb/yd^3
W	3.0	5.0
X	2.4	4.0
Y	1.8	3.0
Z	1.2	2.0

2.1.4 External Alkalis

Concrete may be exposed to alkali salts in service; examples include structures exposed to seawater, which is predominantly composed of sodium chloride (NaCl), or deicing and/or anti-icing salts which might include NaCl, potassium acetate (CH_3COOK) or either sodium acetate (CH_3COONa) or sodium formate (HCOONa).

There are a number of publications that show that sodium chloride from de-icing salts or seawater can aggravate alkali-silica reaction (ASR) in concrete containing reactive aggregates (Chatterji et al., 1987; Nixon et al., 1988; Kawamura and Ichise, 1990; Kawaniura et al., 1994; Berube and Frenette, 1994; Duchesne and Berube, 1996; Sibbick and Page, 1996). However, the extent to which NaCl exposure increases the risk of damaging ASR in the field is not clear and, in good quality concrete, it is likely that any impact is restricted to the region of concrete close to the exposed surface. This needs to be confirmed by testing under field conditions (e.g. concrete exposed to marine environments or de-icing salts).

In recent years, there has been much interest about the impact of potassium acetate (and other acetate/formate solutions) used as anti-icers or de-icers on airfield pavements and, to a lesser extent, bridge decks equipped with automated anti-icing systems. The concerns raised have been spurred by various cases where cracking has been observed on airfield pavements and by laboratory studies that spotlighted the destructive nature of potassium acetate under accelerated testing. Research conducted by Rangaraju and co-workers (Rangaraju and Olek, 2007; Rangaraju et al., 2007) indicate that in mortar or concrete exposed to concentrated (50%) solutions of potassium acetate at elevated temperatures (e.g. 38°C/100°F or 80°C/178°F) there is an increase in pH due to the formation of calcium acetate and, subsequent, increase in the concentration of KOH which exacerbates the attack on reactive silica in the aggregate. Expansion also occurs in concrete without reactive aggregates and this has been linked to the formation of potassium sulfate from calcium sulfo-aluminate phases (Rangaraju and Olek, 2007; Thomas and Hayman, 2011; Hayman et al. 2012). However, little work has been conducted to investigate the impact of these alkali-bearing compounds on concrete under field conditions where they are applied at temperatures at or close to freezing. Under these conditions it is likely that the depth of penetration of the salts into the concrete is limited; however, further work is required to elucidate the precise role of these salts in terms of alkali-aggregate reactions or other forms of deterioration.

Existing standard practices (CSA A23.2-27A, 2019, AASHTO R80-17 and ASTM C1778 -19) increase the level of ASR risk when structures are exposed to external sources of alkali in service and this results in an increase in the level of prevention required if the concrete contains reactive aggregate.

2.1.5 Moisture Availability

Sufficient moisture is required to both sustain the chemical reaction and to provide for the expansion of the gel. It is generally considered that the chemical reaction will cease if the internal relative humidity inside the concrete falls below 80% (Figure 7). Local differences in moisture availability within the same structure can result in very different levels of ASR damage occurring within that structure. Specifically, portions of the structure exposed to a constant or steady source of moisture (e.g., as a result of poor drainage or poor detailing) can exhibit significant ASR-induced damage, while other portions of the structure that remain essentially dry may show little or no damage.

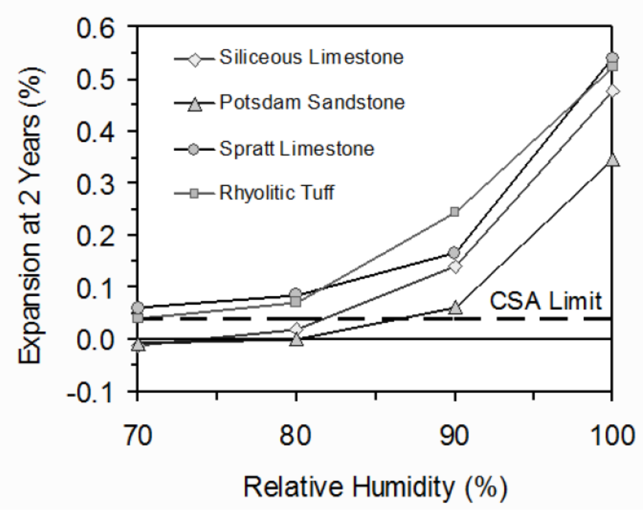


Figure 7. Effect of Relative Humidity on ASR Expansion (Pedneault, 1996)

2.1.6 Interaction with Other Deterioration Mechanisms

Although ASR has rarely caused extreme damage to concrete when it is acting as the sole mechanism of deterioration, it can increase the risk of damage due to other processes such as the ingress of chlorides and subsequent corrosion of embedded steel reinforcement or the action of cyclic freezing and thawing. Furthermore, ASR damage has often been found in association with damage due to delayed ettringite formation (DEF) and this has been linked to ASR reducing the alkalinity of the pore solution which facilitates the release of sulfates from C-S-H (Thomas, 2001; Thomas et al. 2008).

2.1.7 Preventive Measures for Use with Reactive Aggregates

A comprehensive review of preventive measures for minimizing the risk of alkali-silica reaction was recently published by the authors of this report (Thomas et al. 2017b). Measures include the limiting the alkali content of the concrete (discussed in Section 2.1.3), the use of supplementary cementing materials (SCM) and the use of lithium-based compounds.

2.1.7.1 Use of Supplementary Cementing Materials (SCM) for Minimizing the Risk of Expansion due to Alkali-Silica Reaction

The potential use of pozzolans to control ASR dates back as far as the discovery of ASR, having been reported in the first major publication on the phenomenon (Stanton 1940). In this paper, Stanton not only demonstrated that damaging reaction would only occur if there was a sufficient quantity of alkalis in the portland cement and reactive silica in the aggregate, but also that expansion was reduced when a pozzolanic cement was used. Ten years later, Stanton (1950) further demonstrated that partially replacing portland cement with a sufficient quantity of pozzolan (pumicite or calcined shale) eliminated deleterious expansion whereas replacement with similar quantities of ground quartz (Ottawa) sand did not, indicating that the beneficial action of the pozzolan extended beyond merely diluting the cement alkalis. Since the formative work of Stanton (1940; 1950) there have been literally hundreds of publications dealing with the impact of SCM on ASR.

Overall the data available in the literature generally support the concept that almost any SCM can be used to prevent damaging expansion due to ASR provided the SCM is used in sufficient quantity. The amount of SCM required to limit expansion to an acceptable level generally increases with the following (Thomas et al., 2017b; Chappex and Scrivener, 2012):

- A decrease in the silica content (SiO_2) of the SCM,
- A decrease in the alumina content (Al_2O_3) of the SCM,
- An increase in the calcium (CaO) or alkali (Na_2Oe) of the SCM,
- An increase in the alkali content of the Portland cement (Na_2Oe),
- An increase in the reactivity of the aggregate.

The reduction in expansion that is observed when SCMs are used has generally been attributed to the ability of SCMs to reduce the alkalinity (or pH) of the pore solution by incorporation of alkali in the C-S-H that forms as a result of the pozzolanic reaction (Bhatty and Greening, 1978; Rayment, 1982; Uchikawa et al. 1989; Glasser & Marr, 1985; Glasser 1992; Hong and Glasser, 1999; 2002). More recent work has also shown that SCMs high in alumina (e.g. metakaolin, slags and certain fly ashes) also are more effective at reducing expansion due to ASR owing to the presence of alumina in pore solution that subsequently reduces the dissolution of silica from the aggregate. The creation of more C-A-S-H will also lower pore solution alkalinity, creating another benefit that reduces silica dissolution.

Figure 8 and Figure 9 show, respectively, the impact of varying amounts of different SCMs on the pore solution alkalinity (OH^- concentration) of pastes and on the expansion of concrete containing reactive (Spratt) aggregate. These data confirm the influence of SCMs in terms of reducing the availability of alkalis which in turn reduces ASR expansion.

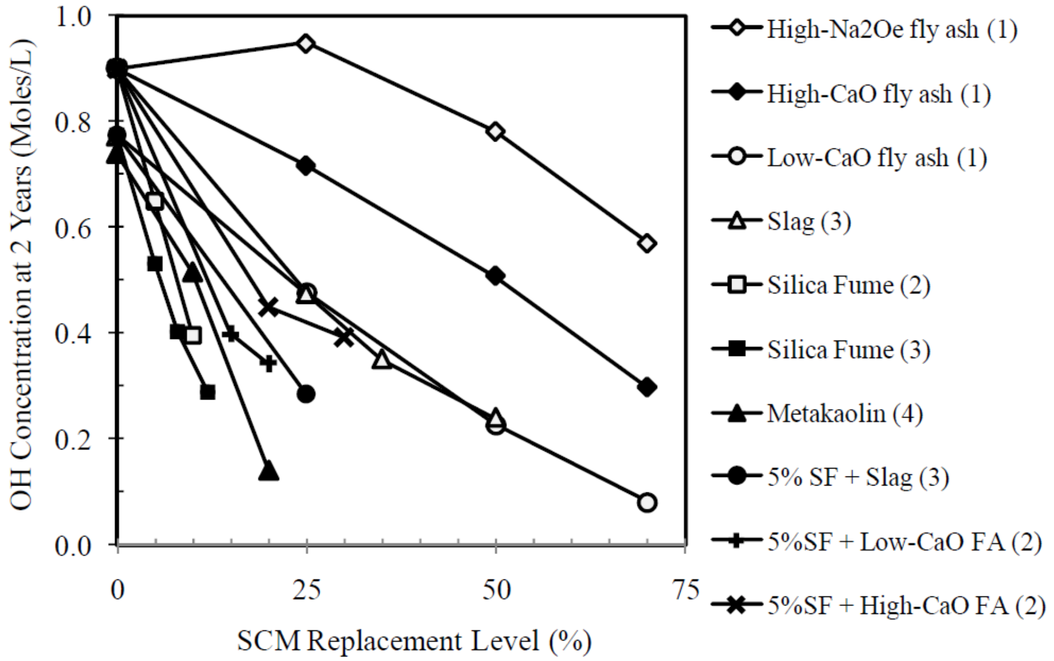


Figure 8. Effect of type and amount of SCM on pore solution composition (Shehata et al. 1999; Ramlochan et al. 2000; Bleszynski 2002; Shehata and Thomas 2002)

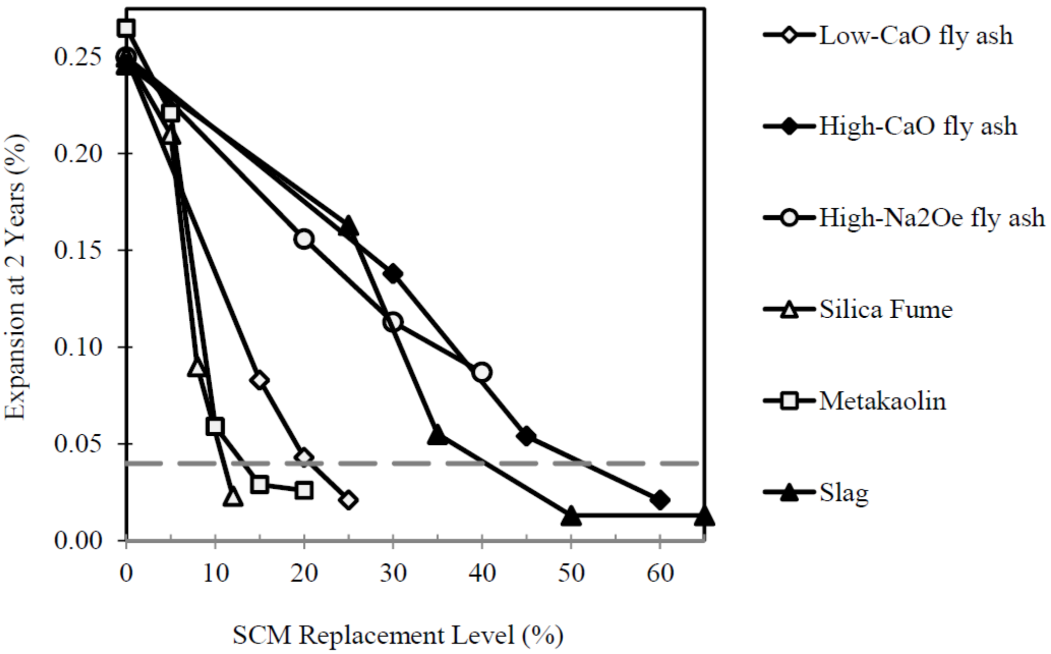


Figure 9. Effect of SCMs on two-year expansion of concrete containing siliceous limestone (Shehata and Thomas 2002; Ramlochan et al. 2000; Thomas and Innis 1998)

The amount of SCM required to prevent damaging ASR expansion generally falls in the ranges shown in Table 2 (modified from Thomas and Folliard, 2007). However, the level of SCM required may exceed these values under exceptional conditions (for example, extremely reactive aggregate, high alkali availability in concrete – including alkali contribution from aggregates, concrete exposed to high concentrations of alkali in service, critical structure with extended service life). The dependence on the amount of SCM required on the reactivity of the aggregate is shown in Figure 10 for various aggregates tested with fly ash and silica fume.

Natural pozzolans (such as volcanic ash) can also be used to control expansion due to ASR; however, it is difficult to make a general statement about the level of pozzolan required as the composition of natural pozzolans varies widely which means that individual sources need to be tested to determine their efficacy.

Table 2. Required levels of SCM

Type of SCM	Level required (%)
Low-calcium fly ash (< 8% CaO)	20 to 30
Moderate-calcium fly ash (8 – 20% CaO)	25 to 35
High-calcium fly ash (> 20% CaO)	40 to 60
Silica fume	8 to 15
Slag	35 to 65
Metakaolin	10 to 20

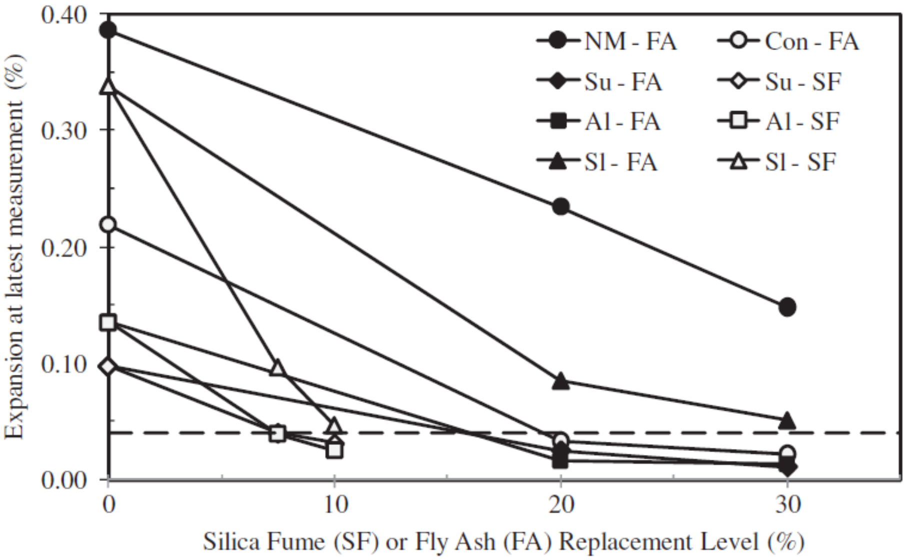


Figure 10. Effect of aggregate type on the amount of silica fume (SF) or fly ash (FA) required to control ASR expansion (Fournier et al., 2004). NM, Con, Su, Al and Sl are different aggregates. FA and SF are fly ash and silica fume, respectively.

2.1.7.2 Use of Lithium-Based Admixtures for Minimizing the Risk of Expansion due to Alkali-Silica Reaction

The ability of lithium to control deleterious expansion due to alkali-silica reaction (ASR) in mortar and concrete was first demonstrated by McCoy and Caldwell (1951) who showed that the amount of lithium required to control expansion was a function of the availability of other alkalis (Na + K) in the system, and they concluded that the expansion of mortar bars containing reactive Pyrex glass could be effectively suppressed provided that the lithium-to-sodium-plus-potassium molar ratio was greater than 0.74, i.e., [Li]/[Na+K] > 0.74. Since then, there have been numerous studies which corroborate this earlier discovery (see review by Feng et al. 2005).

The precise mechanism by which lithium controls ASR is not known, although many theories have been put forward (Feng et al. 2005). The simplest and most commonly used explanation is that lithium salts will react with reactive silica in a similar way to sodium and potassium salts, but the reaction product is an insoluble lithium silicate with little propensity to imbibe water and swell. The lithium silicate forms around reactive aggregate particles and protects the underlying reactive silica from “attack” by alkali hydroxides.

Research at Laval University in Canada (Tremblay et al. 2007) has highlighted the influence of aggregate type on the amount of lithium required to suppress expansion due to ASR. Figure 11 shows the 2-year expansion of concrete prisms with 12 different reactive aggregates and 1 non-reactive aggregate (NF), and various levels of lithium (standard dose is [Li]/[Na+K] = 0.74). For 6 of the 12 aggregates 75% to 100% of the standard dose was sufficient to control expansion (≤ 0.040% at 2 years). For 3 of the aggregates 125% to 150% of the standard dose was required;

however, for the remaining 3 aggregates expansion could not be controlled even at 150% of the standard dose. As the effectiveness of lithium appears to be extremely aggregate dependent, it is not possible to prescribe a single dose for controlling ASR, and the minimum dose must be determined by testing lithium with the specific reactive aggregate being considered for use. At this point in time there is no consensus regarding the appropriateness of accelerated tests for determining the correct lithium dose, and it is recommended that the concrete prism test is used for this purpose.

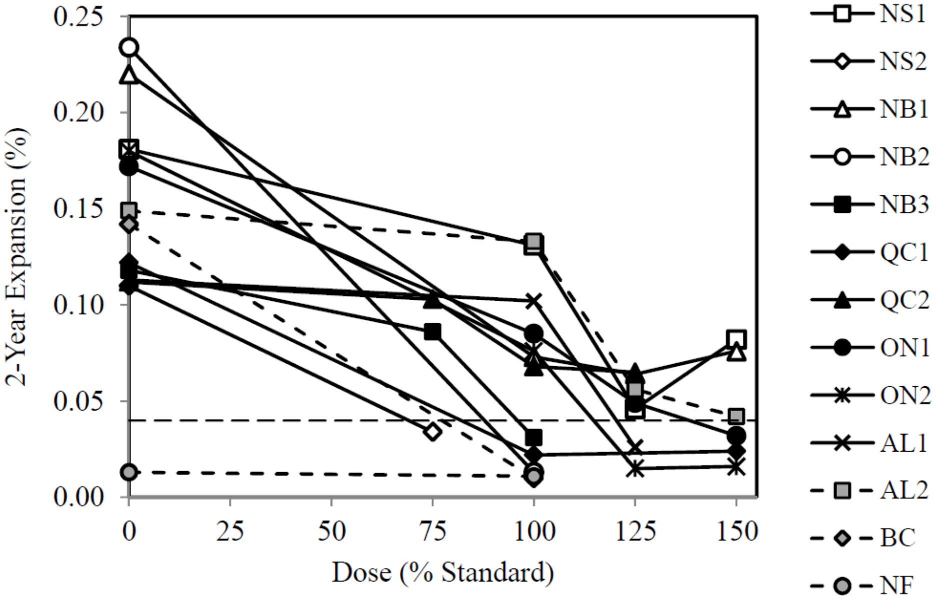


Figure 11. Effect of Lithium Dose on the Expansion of Concrete with Different Reactive Aggregates (from Tremblay et al. 2007)

2.2 <u>ASR Test Methods</u>

This section provides a comprehensive review of the most recent development in ASR test methods for aggregate reactivity and the efficacy of preventive measures. The literature review addresses the aggressive nature of laboratory tests, the impact of alkali content of cements, the cement content and the adequacy of the SCMs in mitigating ASR. There is an emphasis on various laboratory tests, including those currently being investigated at RILEM and other international organizations.

2.2.1 Current Standardized Test Methods used in North America

This section briefly describes the standardized test methods available in the United States and Canada. In addition to describing each method, comparisons are made between the various methods, including comparisons between American (AASHTO/ASTM) and Canadian (CSA) methods. Correlations between the various tests are provided, along with comparisons between the various accelerated laboratory tests and outdoor exposure block data.

2.2.1.1 ASTM C1260/AASHTO T303/CSA A23.2-25A

The accelerated mortar bar test (AMBT) was originally invented in South Africa by Oberholster and Davies for detecting potentially deleterious alkali-silica reactivity of aggregates (Oberholster and Davies, 1986). In this test method mortar bars measuring 25 x 25 x 285 mm (1 x 1 x 11.25 in) are cast using fine aggregate or a crushed coarse aggregate. The fine aggregate is combined in a specific gradation. Bars are cast and then cured for 24 hours at 20 ºC (68 ºF). After 24 hours the bars are demolded and then immersed in tap water and placed in an 80 ºC (176 ºF) oven for 24 hours. After 24 hours (48 hours after casting) the initial measurement is taken, and the bars are then transferred to 1 N NaOH that is already at 80 ºC (176 ºF). Length change measurements are made periodically over the next 14 days. This test method is generally considered the most severe method for assessing the potential for alkali-silica reactive aggregates. It is known to produce both false positives and false negatives. ASTM C1778 recommends that it is best to verify that the results of aggregate testing in C1260 and C1293 produce the same predictive outcome (e.g. both exceed the expansion limit of the respective test) before it can be used with confidence to predict the efficacy of mitigation methods. ASTM C1778 also contains cautionary language about the types of aggregates that are known to produce erroneous results in the test method. Much of this is due to the crushing and/or washing procedure to produce a fine aggregate which would be required to evaluate a potentially reactive coarse aggregate.

When comparing the ASTM and CSA versions of the AMBT, the most significant difference is that an expansion limit of 0.10% is used in ASTM C1260 to distinguish between reactive and non-reactive aggregates, whereas CSA A23.2-25A an expansion limit of 0.150%. Additionally, CSA A23.2-25A specifies an alkali content for the portland cement of 0.90% ± 0.10% Na_2O_e, whereas ASTM C 1260 does not require a specific portland cement.

2.2.1.2 ASTM C1567/CSA A23.2-28A

ASTM C1567 is nearly identical to ASTM C1260 with the only exception being that a portion of the portland cement is replaced with the level of SCM under interest for the test method (e.g. 25% of the portland cement is replaced with fly ash). The test is then run in an identical manner to C1260 and an expansion limit of 0.10% is used at 14 days to determine the efficacy of the SCM under evaluation. Some agencies recommend extending this test method to 28 days however this has not been shown to provide a better correlation to exposure blocks or field exposed concrete. Due to the aggressive nature of this test (1 N NaOH) it is known that any mortars containing aggregates with potentially reactive silica are likely to expand if the prisms are kept long enough in the 1 N NaOH as the soak solution simply overwhelms the mortar prisms and masks the beneficial effects of having SCMs. Further, it is known that due to the aggressive nature of the test method it does not correlate well with outdoor exposure block results as shown in Figure 12.

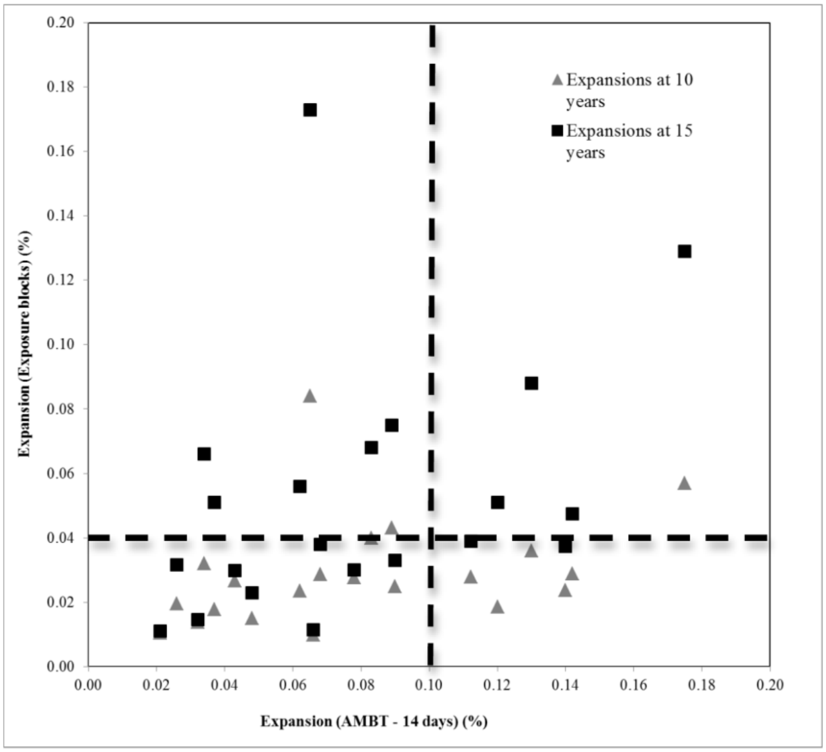


Figure 12. Expansion of concrete containing SCMs in outdoor exposure blocks at 10 or 15 years compared to 14-day accelerated mortar bar test in the Ottawa, Canada exposure site. Data shown are for unboosted (e.g. 0.95% Na_2O_{eq}) blocks and standard AMBT bars. (Ideker et al., 2012)

When comparing the two AMBT tests aimed at evaluating SCMs, there is little difference between ASTM C1567 and CSA A23.2-28A, with the exception of requisite w/cm ratios. ASTM C1567 retains the 0.485 w/cm of ASTM C1260 while the CSA A23.2-28A standards specifies the following: “For natural fine aggregates, a water-to-cementitious materials ratio equal to 0.44 by mass shall be used. For crushed coarse aggregates or manufactured sands, a water-to-cementitious materials ratio equal to 0.50 by mass shall be used.” (CSA A23.2-28A-19)

2.2.1.3 ASTM C1293/CSA (A23.2-14A)

ASTM C1293, also known as the concrete prism test, allows for the testing of a concrete mixture cast in 75 x 75 x 285 mm (3 x 3 x 11.25 in) prisms. The prisms are cured for 24 hours after casting and then placed above water in a sealed container with a wicking material placed around the inside of the container to maintain near 100 % RH. The prisms are measured periodically for length change and an expansion limit of 0.04% is used at one year to determine the potential for aggregate reactivity. If a preventive measure such as incorporation of SCM or lithium nitrate is evaluated, the test duration is extended to two years while the expansion limit of 0.04% is retained. This test is considered to be the most reliable for assessing aggregate reactivity. However, the test method has come under question in recent years due to the disconnect between the two-year prediction for preventive measures compared to outdoor field exposure blocks as illustrated in Figure 13.

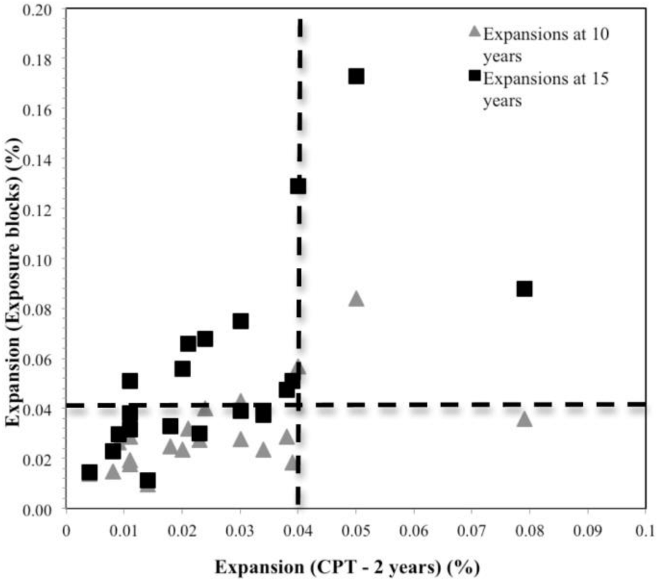


Figure 13. Expansion of concrete containing SCMs in outdoor exposure blocks at 10 or 15 years compared to the 2-year concrete prism test in the Ottawa, Canada exposure site. Data shown are for unboosted (e.g. 0.95% Na_2O_{eq}) blocks and boosted (e.g. 1.25% Na_2O_{eq}) prisms. (Ideker et al., 2012)

In Figure 13, the correlation between outdoor exposure blocks and the 2-year concrete prism test appears generally good. However, after 15 years about half of the mixtures that were predicted to be mitigated effectively using the 2-year concrete prism test started showing deleterious expansion in the outdoor exposure blocks. This trend has been highlighted for the exposure site in Austin, Texas as well in other sections of this report. While the concrete prism test remains reliable for assessing aggregate reactivity the disconnect between the blocks and the 2-year CPT is of great concern. It points to the need to develop a more reliable and rapid test for assessing the efficacy of mitigation options.

ASTM C1293 and CSA A23.2-14A are the standard concrete prism test for assessing potentially aggregate reactivity. CSA A23.2-28A contains provisions for evaluating preventive measures in either the concrete prism test (first half of the standard) or in the accelerated mortar bar test (second half of the standard). The main difference in the two versions of the concrete prism test is that the ratio of coarse to fine aggregate is specified as 60:40 for normal weight aggregates in CSA A23.2014A whereas a coarse aggregate volume fraction of 0.70 is specified in ASTM C1293. In ASTM C1293 the mixture proportions are calculated and the only remaining volume fraction after the cementitious materials content, air content, water content and coarse aggregate content is determined is then filled with fine aggregate.

In the 2019 CSA specification A23.2-28A contains a provision for boosting cement alkalis when the cement under evaluation has an alkali content below 0.80 Na_2O_{eq}. The test method states that when an alkali content less than 0.80 Na_2O_{eq} or when a cementitious materials content of less than 420 kg/m_3 (708 lb/yd_3) is to be evaluated then NaOH should be added to the mixing water to obtain an alkali content 40% above that of the cement alkali content to address the known issue of alkali leaching in the concrete.

2.2.1.4 ASTM C441

ASTM C441, also known as the pyrex mortar bar test involves casting mortar prisms where the alkali-silica reactive aggregate fraction is ground, sieved borosilicate glass. The purpose of the test method is to determine if a supplementary cementitious material has the potential to mitigate ASR. The mortar prisms are stored vertically at 38° C (100 ºF) in a tightly sealed container, over - but not touching, a reservoir of water with a wicking material on the sides of the container. A control set of prisms is cast with high alkali portland cement. Control prisms must have an expansion of 0.25% or greater after 14 days of storage. Subsequent mixtures with the same parent portland cement, but a portion being replaced by SCM, are compared to the control to determine the potential for mitigation. This test method does NOT evaluate how a particular SCM may control the reactivity of a specific aggregate since the aggregate fraction is ground pyrex glass. Therefore, this test should only be used as a screening test or a relative comparison test to evaluate the potential for an SCM to control ASR. Further testing with the SCM and potentially reactive aggregate in question must be done.

2.2.1.5 AASTHO T380

The miniature concrete prism test (MCPT) is a hybrid approach between ASTM C1293 and C1260. The method is specified as AASHTO T380. In this test, concrete prisms measuring 50 mm x 50 mm x 285 mm (2 x 2 x 11.25 in) are cast using a maximum aggregate size of 12.5 mm (0.5 in), a w/cm of 0.45 and a coarse aggregate volume fraction of 0.65. A cement content of 420 kg/m^3 (708 lb/yd^3) is specified. The prisms are moist cured for 24 hours at 23 +/- 2°C (73.4 °F) and then demolded and placed in a water bath at 60 °C (140 °F) for 24 hours. After this time, an initial measurement is taken and the bars are then placed in 1N NaOH, already at 60 °C (140 °F). Length change measurements are made periodically, and the current suggested expansion limits are at 56 days for aggregate reactivity. It was found that the results from MCPT and CPT method correlated very well in characterizing the aggregate reactivity, while a poor correlation was observed between the results of MCPT and AMBT methods (Rangaraju et al., 2016). If mitigation options are assessed the only change is that a desired portion of the portland cement is replaced with SCM being ground granulated blast furnace slag, fly ash or silica fume.

Three classifications (at 56 days) are used in AASHTO R 80 for the efficiency of mitigation in the MCPT as shown in Table 3. Work done by Latifee and Rangaraju (2014) investigated eight different fly ashes with different chemistries as well as slag, silica fume and metakaolin to determine the possibility that the MCPT could be used to determine the efficacy of ASR mitigation measures. Correlation to ASTM C1293 test results was done for all mixtures. In this study, no benchmarking to outdoor exposure blocks, or field structures was done.

Table 3. Expansion limits in AASHTO T380

Efficiency of Mitigation	% Expansion at 56 Days (8 weeks)
Effective	< 0.020%
Uncertain *	0.020% - 0.025%
Not effective	> 0.025%

*Recommend retest with MCPT using a higher dosage of mitigation

Latifee and Rangaraju examined the influence of soak solution normality on concrete mixtures containing the Spratt reactive limestone coarse aggregate at three different levels including 0.5N, 1.0N and 1.5 N NaOH. They found that beyond 56 days the relationship between expansion of prisms and the soak solution normality was linear. At earlier ages they noted that the impact of 1.0N and 1.5N NaOH was minimal. They recommended a soak solution of 1.00 N NaOH be used for the MCPT test procedure.

The influence of the MCPT soak solution when fly ash was used as a mitigation option was also investigated by Latifee and Rangaraju. In this part of the study 0.5 and 1.0 N NaOH as the host solution. Increasing the soak solution alkalinity increased expansions. An increase in fly ash dosage reduced the ASR expansion more rapidly in MCPT mixtures using a 1.0 N NaOH compared to 0.5N NaOH. Further, as the CaO content of the fly ash increased, the expansion occurred more rapidly in 1N NaOH than in 0.5 N NaOH soak solution.

Latifee and Rangaraju also investigated the influence of soak solution normality on job mixtures by doing a series of different alkalinities at 0.45N, 0.70N and 1.00N NaOH. The aggregate used in this part of the study was the Spratt aggregate. The predicted alkalinity of the soak solution was based on work by Stark and Diamond (Helmuth et al. 1993). This work showed that the test method was able to distinguish between the three different normalities. The results also showed that at early ages (up to 28 days) the relationship between expansion percent and the soak solution concentration was linear. However, at later ages this deviated. In the lowest normality soak solution, the expansion was observed to be slow and gradual whereas it was more rapid in the 1 and 0.70 N solution.

In further work on job mixtures two field mixtures were replicated in the laboratory. One mixture that used 15% class C ash (27% CaO) showed signs of ASR distress in an airfield taxiway after only 5 years of service. Using a matched pore solution as the soak solution there was virtually no difference between the control and the mixture with 15% class C fly ash, indicating no mitigation would be expected int eh field. The soak solution for MCPT was 0.55 N NaOH and was based on 100% OPC, and thus a conservative approach. The other mixture used 40% grade 120 slag and the same soak solution (0.55 N NaOH) as before. The control expanded significantly whereas the mixture with 40% slag was well below the proposed MCPT expansion limit at 56 days (or even 84 days). This mixture has shown no signs of deterioration the field. This indicates that there is promise for the use of this test method to evaluate job mixtures. Research on a broader suite of aggregates, SCMs and detailed evaluation of how much of the cementitious material should be accounted for in the matched pore solution should be undertaken before a final recommendation is made.

Only one study has done preliminary benchmarking of the method to field exposure blocks (Chopperla et al., 2019). In this study, a subset of mitigated ASR mixtures that were shown to pass ASTM C1293 (2 year) or ASTM C1567 (14 day) but that exhibited deleterious expansion and cracking in outdoor field exposure blocks were chosen. Figure 14 shows the results of MCPT testing (Chopperla et al., 2019).

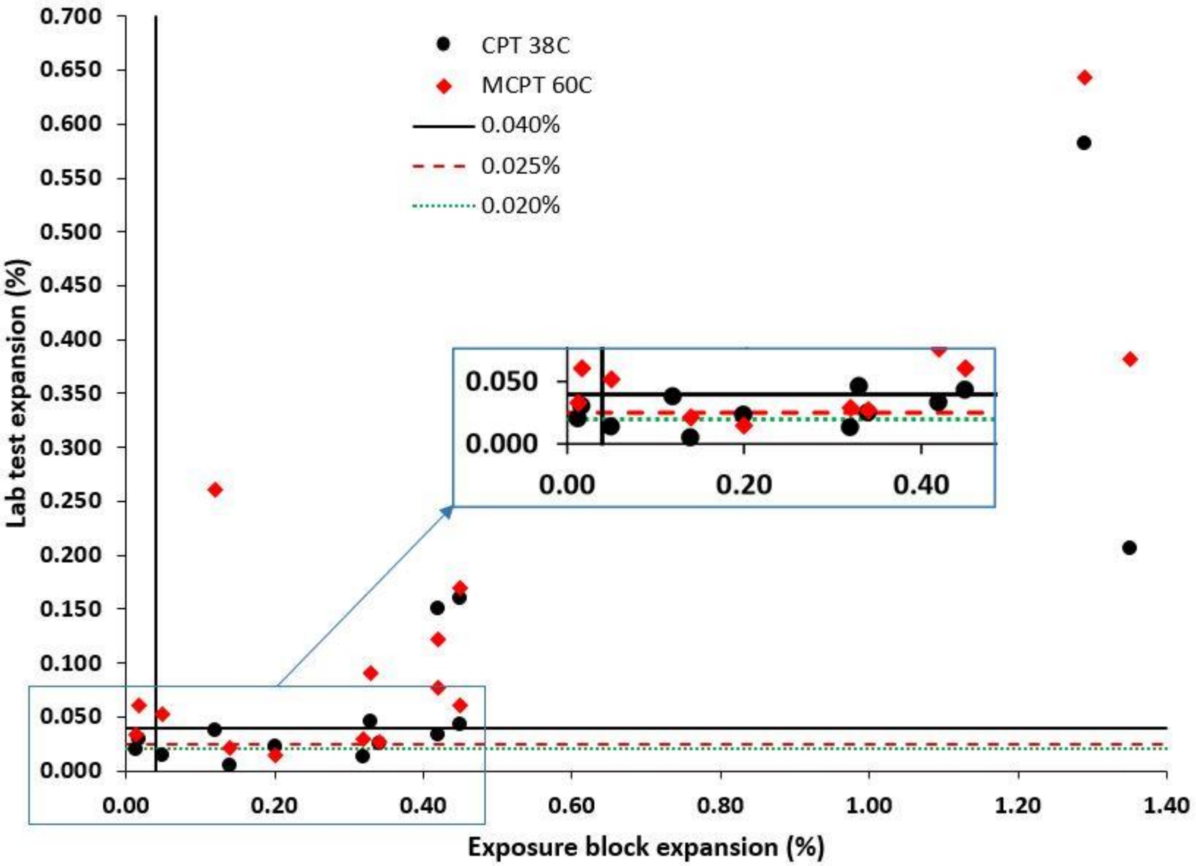


Figure 14. Results of AASHTO T380 testing on mixtures containing alkali-silica reactive aggregates with mitigation options after 56 days of expansion. These mixtures were shown to pass C1293 (2 year) and C1567 (14 day) but exhibited deleterious expansion and cracking in outdoor exposure blocks.

Of the 15 mixtures evaluated using the MCPT only one (1) mixture was shown to be below the expansion limit of 0.020% after 56 days in the test compared to six (6) of the mixtures evaluated in the CPT. Again, the majority of the mixtures evaluated in this testing program showed deleterious expansion in the field. Two mixtures (red diamonds that are below the exposure block expansion limit of 0.04%) are only two years old at the time of writing this report. The MCPT predicts that both of these mixtures will eventually show expansion and cracking the outdoor exposure blocks.

This preliminary work indicates that the MCPT has a better correlation to outdoor exposure blocks compared to either the CPT (2 years) or AMBT (14 days) for assessing the efficacy of SCMs. For the mixtures in this study an expansion limit of 0.020% at 84 days may be a more appropriate limit for mixtures with SCMs. However, further work to conclusively determine this is needed. This is one of the most promising test methods for further exploration on a larger suite of aggregates and SCM types.

While this test method shows promise for future investigation owing to its better correlation with field exposure blocks there are several challenges that remain and merit further work. First, the test method, in its current form, is still not capable of testing job mixtures. Due to the immersion in 1 N NaOH changes in alkali content/loading will likely be overwhelmed by the aggressive nature of the storage solution. One way to overcome this may be to use a soak solution where the normality is matched to the pore solution for that particular mixture building off of work by Latifee and Rangaraju (2014). A simple mathematical prediction could be used to produce the matched solution.

A simple mathematical prediction could be used to produce the matched solution. Thomas and Shehata proposed the following equation based on experimental data:

$[OH^-] = 0.7 * Na_2O_{eq}$ Equation 1

(Thomas et. al, 2006)

Kawabata et. al, suggested modifications to this equation to account for the presence of SCMs and different w/cm, however much caution was given that the literature contained a wide variation of pore solution OH concentrations if samples were paste or concrete and depending the w/cm as well as the presence of clay minerals or releasable alkalis from aggregates.

$[OH^-] = 0.386 * Na_2O_{eq}(w/cm)$ Equation 2

(Kawabata, et al., 2018)

This approach is being explored in Switzerland and is further outlined in Section 2.2.3.4. While the test method does specify a coarse aggregate, the maximum size is 12.5 mm which is slightly lower than that found in many highway construction mixtures (19 mm or slightly larger is more typical). This may limit the representativeness of the concrete in this test method.

The storage temperature of 60 ºC (140 ºF), while providing an acceleration of the reaction is not so high as to be unrealistic. The issues with solubility of silica at high temperature and sulfate being drawn into solution at the expense of hydroxyl ions is much less significant at 60 C compared to 80 C and this provides an advantage over test methods at higher temperatures. The immersion in a soak solution also prevents the leaching issues that are a continued problem the concrete prism test.

2.2.1.6 CRD-C662

CRD-C662 is the test method for “Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials, Lithium Nitrate Admixture and Aggregate (Accelerated Mortar-Bar Method)”. This test method is an Army Corp of Engineers standard test method to evaluate the effectiveness of lithium nitrate for mitigating ASR. This test method is similar to the AMBT (ASTM C 1260); However, two major items are different between the test methods which include: 1) CRD allows the use of lithium nitrate for mitigation and 2) the expansion limit is taken at a different age. The lithium nitrate can be placed between 50-150% of the standard lithium admixture dosage and lithium is placed in the alkaline soak solution based on the dosage placed in the mortar bar. The standard AMBT takes the final expansion measurement after 14 days in the soak solution while the FAA uses an expansion limit of 0.10% taken at 28 days and the Corp of Engineers use 0.08% at 28 days. Length change measurements are taken every 2-3 days over the 28 days the bars are in the soak solution.

2.2.1.7 AASHTO T 379

AASTHO T 379 is the Standard Method of Test for Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) for Concrete Specimens with Damage from the Alkali-Silica Reaction (ASR). This test method determines the nonlinearity of an ASTM C1293 concrete prism that progresses with ASR deterioration over time. The concrete specimen is excited through a fundamental transverse mode of vibration by a low amplitude impact. The vibration is measured with an accelerometer and recorded with an oscilloscope. The sample is then struck at least 10 times with a light hammer and time domain signals are recorded. The data is then processed to measure the frequency and amplitude at the different time domains. The nonlinearity parameter, n, is determined by graphing the normalized frequency shift against signal amplitude.

At least three specimens per mixture should be evaluated for the nonlinearity parameter. Initial measurements are taken 24 hours after casting and subsequent measurements are taken every couple of weeks or months depending on reactivity. A more reactive aggregate is measured more often than a slower reacting aggregate. Similar to ASTM C1293, the mixture bucket is removed from the oven a day prior to measurements. Figure 15 shows the setup of the concrete prism connected to the oscilloscope and accelerometer. During each measurement time, 10 impact recordings occur with each subsequent impact increasing. After signal processing, the nonlinear parameter is determined. A nonlinear parameter value of 0.2 or more during the 12-month test period may be considered alkali-reactive. A value between 0.05 and 0.2 suggests that the aggregate should be further evaluated. This test method can occur simultaneously with ASTM C1293 since the same prisms are evaluated. Figure 16 shows the nonlinear parameter for three sets of reactive mixtures (Lesnicki et al. 2011). The S1 aggregate (Placitas, New Mexico) shows the highest non-linear parameter followed by S2 aggregate (Spratt) and the non-reactive mixture had a nonlinear parameter near 0. The nonlinearity occurs due to the cracking and debonding of constituents within the concrete (Lesnicki et al. 2011).

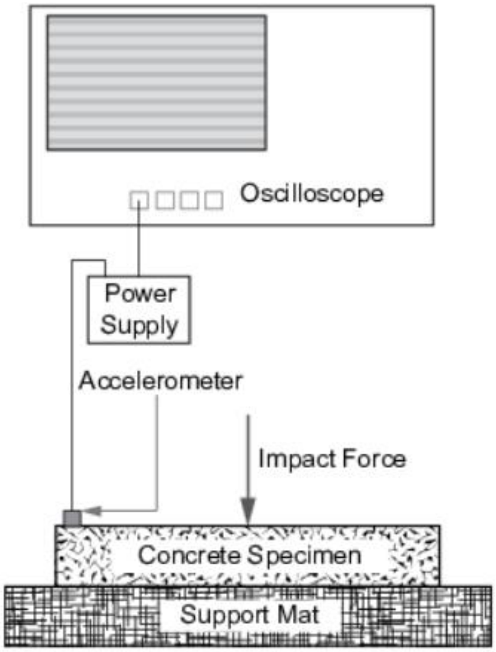


Figure 15. Test setup for nonlinear impact resonance acoustic spectroscopy (NIRAS)

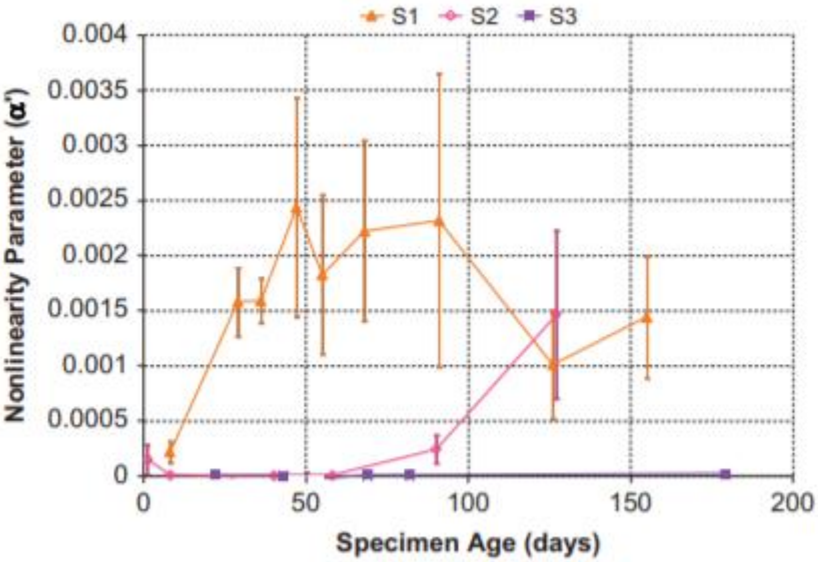
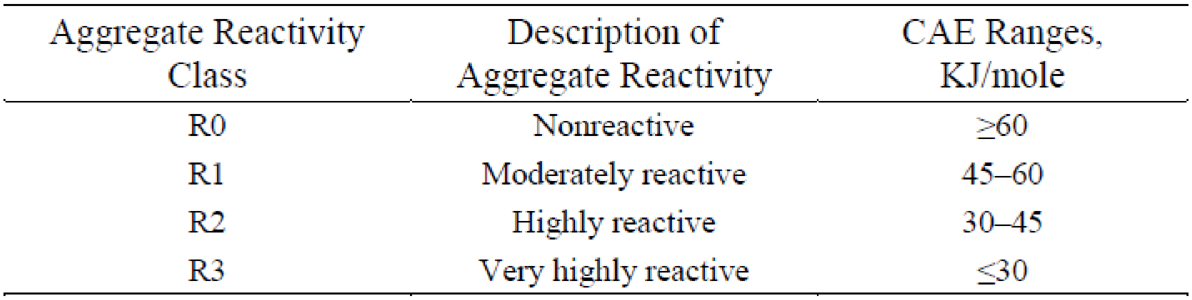


Figure 16. Nonlinearity parameters for three sets of reactive mixtures

2.2.1.8 AASHTO T 364

AASHTO T 364 is the Standard Method of Test for Determination of Composite Activation Energy of Aggregates due to Alkali-Silica Reaction (Chemical Method). This test method determines the potential reactivity of aggregates by measuring the activation energy from placing aggregates in simulated pore solutions and placing this system into a dilatometer device to which measures the volume change. A LVDT is used to measure the volume change. Fine or coarse aggregates can be placed within the device. The test method provides a gradation for both coarse and fine aggregates. The aggregates are washed and dried in an oven to constant mass prior to testing. Three aggregate samples between 3.6 to 4.1 kg (8 to 9 lb) are evaluated at three testing temperatures 60,70, and 80ºC (140,158 and 176 ºF). Once the aggregates and solution are in the device, they are each placed at the different temperatures for up to 100 hours each. Initial thermal expansion is subtracted from the LVDT measurement and then a displacement is measured from right after temperature equilibrium to about 90 hours. With the LVDT measurement, the percent volume change of solution due to ASR is used to calculate activation energy. Once an activation energy is determined it can be used to determine the aggregate reactivity. Table 4 shows how the activation energy and aggregate reactivity (based on AASHTO R80) correlate.

Table 4. Correlation between CAE and aggregate reactivity class from AASTHTO T364



Aggregate Reactivity Class	Description of Aggregate Reactivity	CAE Ranges, KJ/mole
R0	Nonreactive	≥60
R1	Moderately reactive	45–60
R2	Highly reactive	30–45
R3	Very highly reactive	≤30

2.2.2 RILEM Test Methods

2.2.2.1 Introduction

Considering the proliferation of test procedures for evaluating the potential alkali-reactivity of concrete aggregates in different regions in Europe, RILEM TC 106 (*Alkali Aggregate Reactions - Accelerated Tests*) (1988-2001) was formed with the objective of making recommendations on test methods that would be reliable, mimicking field experience, sufficiently accelerated to be practically useful, and internationally accepted. TC-106 published draft RILEM Recommendations for an accelerated mortar-bar expansion test (AAR-2) and a concrete prism expansion test (AAR-3) in 2000 (RILEM 2000). In addition, the committee worked towards the development of a procedure for petrographic examination (AAR-1), of an accelerated concrete prism test (AAR-4) and of a special procedure for the evaluation of carbonate aggregates. During that period, the reliability of AAR-2 and AAR-3 methods was assessed with local/regional aggregates in different parts of Europe, an interlaboratory study on AAR-2 and AAR-3 was carried out and sources of reference high-alkali cements and non-reactive aggregates established.

RILEM TC 191-ARP (*Alkali Reactivity; Prevention, Assessment, Specification and Diagnosis*) (2001-2006) integrated the methods developed under TC-106 into an assessment system (AAR-0) and worked on the principles/options for the specification to avoid damage from alkali-reactions (RILEM 2003a). Other achievements of TC-191 included the publication of AAR-1 as a draft RILEM recommendation (RILEM 2003b), the completion of the AAR-4 procedure, and the development of a preliminary screening method for carbonate aggregates (AAR-5) and of the international specifications to minimise damage from AAR in Concrete, i.e. Part 1—ASR (AAR 7.1) and Part 2 – ACR (7.2) (RILEM 2016). During this period, the PARTNER project, an EU funded project aiming to assess the RILEM methods as the basis for European (CEN) standardization, was also undertaken (Lindgard et al. 2010).

RILEM TC219-ACS (*Alkali-Aggregate Reactions in Concrete and Structures*) (2006-2014) incorporated the lessons of the PARTNER project into the RILEM methods, completed the development of AAR-7, and prepared the suite of methods/specifications for publication in a State-of-the-Art report (RILEM 2016). In addition, a worldwide petrographic atlas of reactive aggregates was produced (Fernandes et al. 2016) and work was initiated on the development of a method for assessing potential alkali contribution by aggregates (AAR-8) and of a performance test for specific concrete mixtures (AAR-10).

RILEM TC-258-AAA (*Avoiding Alkali Aggregate Reactions in Concrete - Performance Based Concept*) (2014-2019) is currently finalizing and validating the performance testing concepts for avoiding AAR in future structures (AAR-10 to AAR-13). It also looks at exposure site investigations to assist in validating accelerated laboratory test methods, and finalizes the development of a method for determining potential alkali release from aggregates (AAR-8).

In summary, the list below includes the relevant RILEM Recommended methods of test for aggregates and RILEM Recommendations (RILEM 2016 and updates):

Guides, specifications and test methods

- AAR-0: Outline Guide to the Use of RILEM Methods in Assessments of Alkali-Reactivity Potential of Aggregates;
- AAR-1.1: Detection of Potential Alkali-Reactivity - RILEM Petrographic Examination Method;
- AAR-2: Detection of Potential Alkali-Reactivity - Accelerated Mortar-bar Test Method for Aggregates;
- AAR-3: Detection of Potential Alkali-Reactivity - 38 °C. Test Method for Aggregate Combinations using Concrete Prisms;

- AAR-4.1: Detection of Potential Alkali-Reactivity - 60 °C. Test Method for Aggregate Combinations using Concrete Prisms;
- AAR-5: Rapid Preliminary Screening Test for Carbonate Aggregates;
- AAR-7.1: International Specification to Minimise Damage from Alkali Reactions in Concrete; Part 1—Alkali-Silica Reaction;
- AAR-7.2: International Specification to Minimise Damage from Alkali Reactions in Concrete; Part 2—Alkali-Carbonate Reaction;
- AAR-7.3: Preliminary International Specification to Minimise Damage from Alkali Reactions in Concrete; Part 3—Concrete Dams and Other Hydro Structures;

Documents under development (i.e. not yet published):

- AAR-8: Determination of Alkalis Releasable by Aggregates in Concrete;
- AAR-10: Determination of Binder Combinations for Non-reactive Mix Design Using Concrete Prisms – 38 ^{o}C test method;
- AAR-11: Determination of Binder Combinations for Non-reactive Mix Design or the resistance to Alkali-Silica Reaction of Concrete Mixes Using Concrete Prisms – 60 ^{o}C Test Method;
- AAR-12: Determination of Binder Combinations for Non-reactive Mix Design or the resistance to Alkali-Silica Reaction of Concrete Mixes Using Concrete Prisms – 60 ^{o}C Test Method with Alkali Supply;
- AAR-13: Application of Alkali-wrapping for Concrete Prism Testing Assessing the Expansion Potential by Alkali-Silica Reaction.

The following sections summarize the main principles and scope of the various RILEM test methods and recommendations listed above.

AAR-0: Outline Guide to the Use of RILEM Methods in Assessments of Alkali-Reactivity Potential of Aggregates

This guide aims at providing guidance for the integrated use (as illustrated in Figure 17)

Test methods

AAR-1.1 - RILEM Petrographic Examination Method

AAR-1.1 describes a procedure to use petrographic methods for classifying concrete aggregates in one of the following classes: Class I—Very unlikely to be alkali-reactive; Class II—Alkali-reactivity uncertain; Class III—Very likely to be alkali-reactive alkali reactive aggregates. A petrographic atlas of reactive rock types was developed to assist petrographers in that task (Fernandes et al., 2016).

The final assessment of reactive constituents/aggregates and acceptance criteria generally follows national or regional experiences. For example, petrography is used to quantify the proportion of reactive particles in concrete aggregate in Denmark, Norway and Sweden, as the basis of specification. The "reliability" of petrographic analysis largely depends on the experience and skill of the petrographer; consequently, the procedure often suffers from poor precision, as was determined through multi-laboratory investigations under the PARTNER program. RILEM thus recommends, in its overall approach AAR-0, to use the petrographic examination as a preliminary exercise to assist in the choice and effective use of other laboratory methods (Nixon and Fournier 2017).

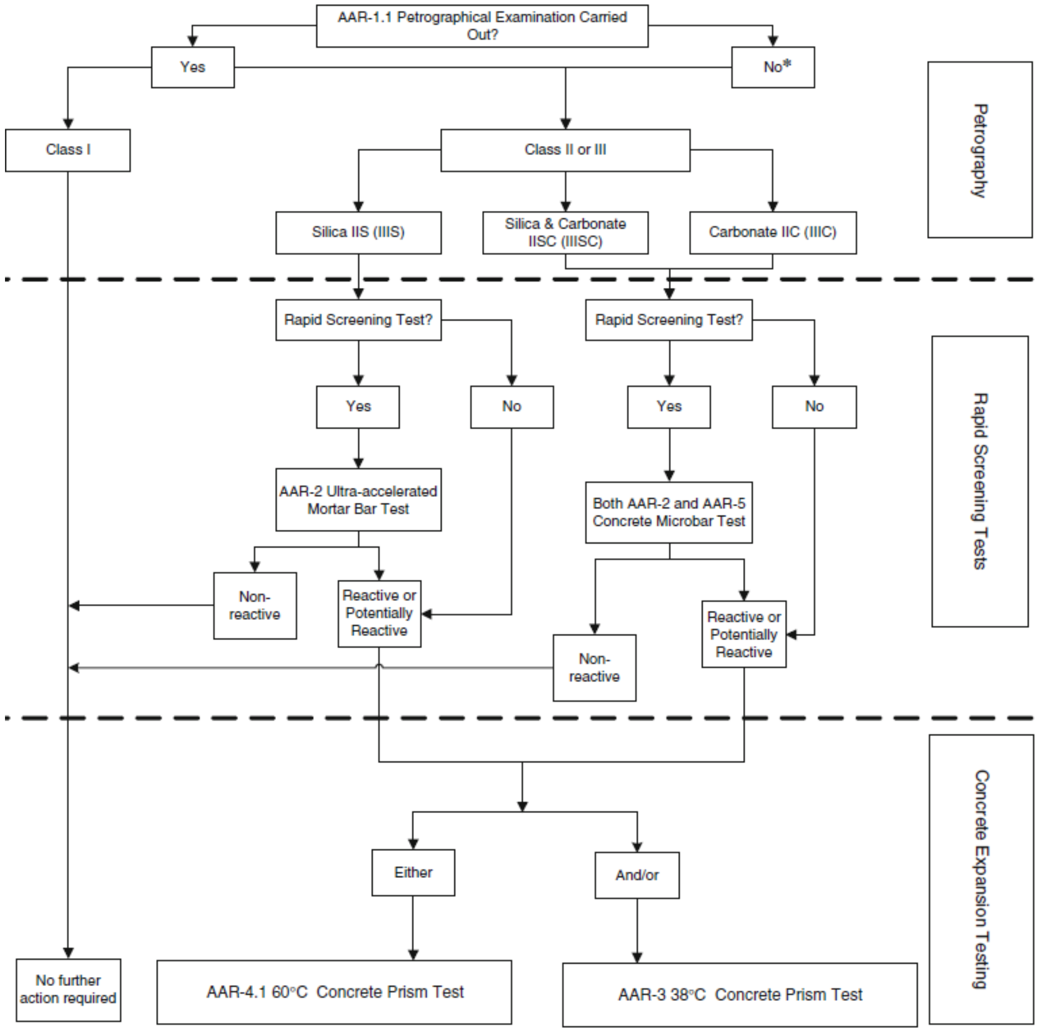


Figure 17. Integrated use of the various RILEM methods for evaluating the potential alkali-reactivity of aggregate combinations for use in concrete (RILEM 2016).

AAR-7: International Specification to Minimise Damage from Alkali Reactions in Concrete; Part 1—Alkali-Silica Reaction (AAR-7.1); Part 2—Alkali-Carbonate Reaction (AAR-7.2)

These documents are meant to provide recommendations for selecting preventive measures in concrete incorporating alkali-silica (AAR-7.1) and alkali-carbonate (AAR-7.2) reactive aggregates. Based on a recent review by Nixon and Fournier (2017), AAR-7.1 describes a step-by-step risk analysis that is somewhat similar to that of ASTM C-1778, ASSHTO R 80-17, CSA A23.2-27A, and Australian specification SA HB 79:2015. The risk analysis recommended in AAR-7 is based on the determination of the degree of reactivity of the aggregates, the nature of the environment to which the structure is exposed, and the expected service life, as shown in Figure 18.

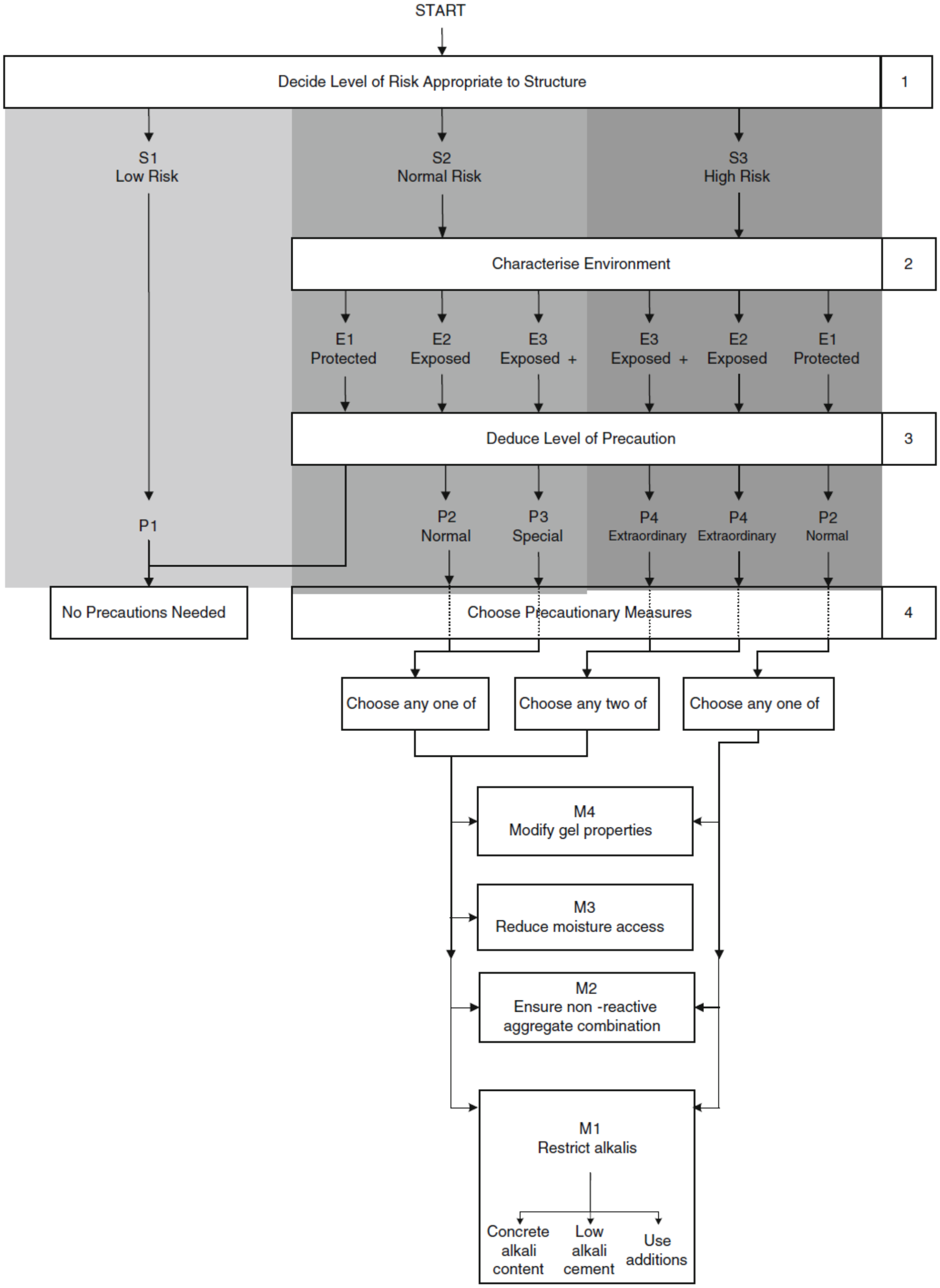


Figure 18. Flow chart summarizing the specification for siliceous aggregates (RILEM 2016)

Test methods

AAR-1.1 - RILEM Petrographic Examination Method

AAR-1.1 describes a procedure to use petrographic methods for classifying concrete aggregates in one of the following classes: Class I—Very unlikely to be alkali-reactive; Class II—Alkali-reactivity uncertain; Class III—Very likely to be alkali-reactive alkali reactive aggregates. A petrographic atlas of reactive rock types was developed to assist petrographers in that task (Fernandes et al., 2016).

The final assessment of reactive constituents/aggregates and acceptance criteria generally follows national or regional experiences. For example, petrography is used to quantify the proportion of reactive particles in concrete aggregate in Denmark, Norway and Sweden, as the basis of specification. The "reliability" of petrographic analysis largely depends on the experience and skill of the petrographer; consequently, the procedure often suffers from poor precision, as was determined through multi-laboratory investigations under the PARTNER program. RILEM thus recommends, in its overall approach AAR-0, to use the petrographic examination as a preliminary exercise to assist in the choice and effective use of other laboratory methods (Nixon and Fournier 2017).

AAR-2: Accelerated Mortar-bar Test Method for Aggregates

This test method is similar to ASTM C 1260 and CSA A23.2-25A. It aims at determining the potential alkali-reactivity of aggregates through the expansion monitoring of mortar-bars immersed in a NaOH solution. Alternative methods are proposed based on the mortar-bar size used. AAR-2.1 uses prisms that are 25 × 25 × 285 mm (2 x 2 x 11.25 in), referred to as a "long thin bars", and AAR-2.2 uses prism that are 40 × 40 ×160 mm (1.57 x 1.57 x 6.30 in), referred to as "short fat bars". Although the test may be used for assessing pessimum behaviour of reactive aggregates, it is not suited for determining potential alkali-reactivity in aggregates containing more than 2 % (by mass) of porous chert and flint (RILEM, 2016).

Bar specimens are manufactured from mortars prepared with the graded aggregate (up to 4 mm) under investigation. After 24 ± 2 h in their moulds, the specimens are demoulded, placed in water in an appropriate container and transferred to an oven at 80 °C (176 °F). After 24 h, the bars are removed from the water, their initial length measured and immediately placed in containers with a 1 N NaOH solution already at 80 °C (176 °F); the containers are then sealed and replaced in the oven at 80 °C (176 °F) for a period of 14 days, period over which their length measurements are taken periodically.

AAR-0 indicates that based on field trials carried out by RILEM on aggregate materials of known reactivity, the following (tentative) criteria are proposed, after 14 days of alkaline storage and based on 25 x 25 x 285 mm (1 x 1 x 11.25 in) bars:

- Expansion < 0.10%: likely to indicate non-expansive material
- Expansion > 0.20%: likely to indicate expansive material
- 0.20 ≥ expansion ≥ 0.10: potentially alkali-reactive

The mean ratio of expansion of short fat to long thin specimens is in the region of 0.75–0.80.

AAR-3: Test Method for Aggregate Combinations using Concrete Prisms (38°C method)

This method is similar to ASTM C 1293 and CSA A23.2-14A. It allows the evaluation of the potential alkali-reactivity of aggregate combinations (Application AAR-3.1) and of the alkali threshold of an aggregate combination (Application AAR-3.2). In AAR-3.1, the proposed aggregate combinations (fixed coarse aggregate-to-fine aggregate ratio (60:40) or optional variable aggregate proportions) is used with a high-alkali cement (0.9 to 1.3% Na_2Oeq) to manufacture concrete at a cement dosage of 440 kg/m^3 (742 lb/yd^3) and a w/c=0.50. NaOH is added to the mixture, when necessary, to raise the total concrete alkali content to 5.5 kg/m^3 (9.3 lb/yd^3) Na_2Oeq. The test prisms, which measure 50 x 50 x 250 mm (2 x 2 x 10 in) are then placed in air-tight plastic containers, which are stored in a temperature-controlled room at 38 °C (100 °F); for a period of 12 months, period over which they are measured periodically.

For AAR-3.2, similar materials, mix designs and procedures are used, except that at least four mixtures are manufactured with alkali levels ranging between 2 and 5 kg/m^3 (3.4 and 8.4 lb/yd^3) Na_2Oeq. The selected concrete alkali contents can be obtained by blending different cements or by the use of sodium hydroxide.

AAR-0 indicates that based on field trials carried out by RILEM on aggregate materials of known reactivity, the following (tentative) criteria are proposed (after 12 months of testing):

- Expansion < 0.05%: likely to indicate non-expansive material
- Expansion > 0.10%: indicate expansive material
- 0.10 ≥ expansion ≥ 0.05: potentially alkali-reactive

Some evidence suggests that a lower criterion, perhaps 0.04 or even 0.03 % at 12-months, might be applicable for some slowly reactive aggregates.

AAR-4.1: Test Method for Aggregate Combinations using Concrete Prisms (60°C method)

This method aims at evaluating the potential alkali-reactivity of aggregate combinations. Concrete prisms are made in accordance with the AAR-3 method but are stored at 60°C for accelerating even further the development of ASR. Similar to AAR-3, the test prisms are removed from the high-temperature cabinet/room 24 hrs prior to expansion measurements.

AAR-0 indicates that based on field trials carried out by RILEM on aggregate materials of known reactivity, the following (tentative) criteria are proposed (after 15 weeks of testing):

- Expansion < 0.03%: indicates a non-expansive material
- Expansion > 0.03%: in the absence of local experience to the contrary, precautions should be taken to minimise the risk of ASR damage to any concrete in which the material is used.

AAR-5: Rapid Preliminary Screening Test for Carbonate Aggregates

This method intends to offer a means of detecting potential alkali-carbonate reactivity in carbonate rocks, especially aggregates containing dolomitic limestone and/or dolomite/dolostone. For that purpose, it is suggested to perform this test in parallel to AAR-2 (accelerated mortar-bar test method). Indeed, alkali-carbonate reactive aggregates will generally not suffer from excessive expansion in the AAR-2 method (size fraction < 4 mm (0.16 in)); on the other hand, AAR-5 uses aggregate particles in the range 4 to 8 mm (0.16 to 0.32 in), which was found to enhance reactivity in such aggregates.

In the case of AAR-5 method, aggregate particles in the range 4 to 8 mm (0.16 to 0.32 in) are mixed with a high-alkali cement (> 1.0% Na_2Oeq), with a proposed w/c of 0.32, to manufacture "short fat bars", with dimensions of 40 x 40 x 160 mm (1.57 x 1.57 x 6.30 in). The use of superplasticizer is allowed if the mix is not sufficiently workable; the amount of water in the admixture then needs to be accounted for in the final water content determination. The bars are then subjected to the same curing and testing regime as in the AAR-2 method.

AAR-0 proposes the following interpretation based on the comparison between the expansion of the aggregate under test in the AAR-2 and AAR-5 procedures (expansion levels based on "short fat bars") (RILEM, 2016):

- AAR-2 > 0.08 %:
  - AAR-5 < AAR-2 = potential ASR
  - AAR-5 ≥ AAR-2 = possible combination of ASR & carbonate reaction
- AAR-2 < 0.08 %:
  - AAR-5 ≥ AAR-2 = possible carbonate reaction
  - AAR-5 < AAR-2 = no further testing

As a complementary method, Grattan-Bellew et al. (2003) suggested to manufacture a companion set of mortar bars using 30% Class F fly ash replacement level. Under those conditions, the use of fly ash would likely reduce/control the development of expansion due to ASR in the specimens while it would not prevent expansion in bars incorporating an alkali-carbonate reaction carbonate rock.

AAR-8: Determination of Alkalis Releasable by Aggregates in Concrete

It is considered by many that one of the critical factors responsible for maintaining expansion in concrete structures due to ASR in the long term is related to alkalis released by the fine and/or the coarse aggregates used in the concrete. This method aims to provide a means for assessing this potential for alkali releasable by concrete aggregates. It must be mentioned that this method is still under investigation through the activities of Work Package 3 of RILEM TC-258-AAA (RILEM 2018a); consequently, changes may still be adopted before its potential adoption and publication as RILEM recommendation.

In this method, the aggregates are processed through crushing (if needed) and/or sieving to produce a grading between 0 and 4 mm (0 and 0.16 in). Companion representative sub-samples of the aggregate thus produced are then immersed in 0.7 M NaOH solution (for measurement of K released) and 0.7 M KOH solution (for measurement of K released) with excess calcium hydroxide (solution-to-aggregate ratio of 4). The test specimens in their containers are then stored in a temperature-controlled oven at 38 °C (100 °F). Twice a week, the containers are removed from the oven and gently agitated (by rolling on a flat table) for 30 seconds. At selected ages (4) over a period of 52 weeks, small samples of the solution are extracted and chemically analyzed by appropriate means for Na and K. The amount of alkalis released are expressed in grams (ounces) of Na_2O, K_2O, and Na_2Oeq per kg (lb) of aggregate.

Studies are currently in progress to determine the multi-laboratory variability of the method using a variety of reactive and non-reactive aggregates.

AAR-10: Determination of Binder Combinations for Non-reactive Mix Design Using Concrete Prisms – 38oC test method

In this draft procedure (RILEM 2018b), concrete prisms are made in accordance with the general principles of AAR-3 method except that the method can be used to evaluate different types of binders (total cementitious materials content of 440 kg/m^3 (742 lb/yd^3); w/b = 0.48; cement ± supplementary cementing materials) with different types of aggregate combinations (e.g. different gradings, combination of reactive/non-reactive coarse or fine aggregates).

The specimens are stored at 38 °C (100 °F) and R.H. > 95%, while larger prisms, with dimensions of 100 x 100 x 450 mm (4 x 4 x 17.7 in), are used to minimize the effects of alkali leaching special precautions are taken to minimize the effect of alkali leaching, i.e. use of larger size prisms. In addition, expansion measurements are taken while the prisms are still hot, immediately after they are removed from the storage room (RILEM 2018b).

The method was designed for two types of applications aiming at the performance assessment of combinations of aggregates and cement/binders at various or specific alkali contents (RILEM 2018b):

- Application 1 (AAR-10.1): Enabling the use of a specific reactive aggregate product together with critical binder combination(s) ("minimum binder requirements") for producing non-reactive concrete.
- Application 2 (AAR-10.2): Enabling the determination of general binder composition together with a (regional;) worst-case aggregate combination for producing nonreactive concrete within that region.

In the case of the Application 1, the scope of testing may be the level of alkali or the level of a SCM in the range of mix design. The test output would then be the maximum alkali level or the minimum SCM content, separately or in combination, for the safe use of the specific aggregate combination. The investigation would typically include 3 – 5 levels of SCM (at a fixed alkali content) or alkali content (at a fixed SCM content), more if both parameters are combined.

In the case of the Application 2, testing would be carried out to establish, for example, the maximum clinker alkali content that could be used with an SCM content (whether as addition or incorporated with the cement) that would meet the acceptance (expansion) limit using a reference aggregate and could thus be used safely with a range of regional/national aggregates (of lower or equal reactivity level) up to that threshold alkali content.

It must be mentioned that this approach is still under investigation through the activities of Work Package 1 of RILEM TC-258-AAA (RILEM 2018b); consequently, changes may still be adopted before its potential adoption and publication as RILEM recommendation.

AAR-11: Determination of Binder Combinations for Non-reactive Mix Design or the resistance to ASR of Concrete Mixes Using Concrete Prisms – 60°C Test Method

This draft test method (RILEM 2018c) is based on a French performance test approach for concrete mixtures (AFNOR 2004a & 2004b) and on both the aggregate test method RILEM AAR-4.1 and the 38°C performance test method RILEM AAR-10 (RILEM 2018b).

Similar to AAR-10, the method was designed for different applications (RILEM 2018c):

- Application 1 (AAR-11.1): evaluate the use of a specific reactive aggregate (different combinations possible) together with critical binder combination(s) (minimum binder requirements) for producing non-reactive concrete;

- Application 2 (AAR-11.2): evaluate the required general binder composition together with a regional worst-case aggregate combination for producing non-reactive concrete;
- Application 3 (AAR-11.3): a selected concrete mix (job mix) is tested to verify its ASR-resistance. The result is limited to the selected aggregate combination, cement type, alkali content of the cement and mix design in the test.

In this procedure, concrete prisms with dimensions of 75 x 75 x 250 mm (3 x 3 x 10 in) are made in accordance with the general principles/approach of AAR-10 (RILEM 2018b) using selected aggregate and binder combination(s). The alkali content of the mixture can be increased at selected levels through the use of NaOH in the mixing water, according to the application selected. The difference here (compared to the AAR-10 test method) is that test prisms are stored in warm (60 °C) and relative humidity conditions as close as possible to 100%. A “reactor-system” is commonly-used in Europe to maintain the test specimens under appropriate testing conditions (Figure 19). Length and mass changes are monitored over a 5 (cement only) or 12 (cement + SCMs) months period. The containers are removed from the storage cabinet (e.g. “reactor”) and stored at 20 ± 2 hours to let them cool down prior to measurements. An alternative measuring procedure without pre-cooling of the prisms is also described, aiming at reducing the effect of alkali leaching from the test specimens.

No limit criteria are currently available for this test procedure. It must be mentioned that this approach is still under investigation through the activities of Work Package 1 of RILEM TC-258-AAA (RILEM 2018c); consequently, changes may still be adopted before its potential adoption and publication as RILEM recommendation.

Figure 19. Reactor generating 60 °C (140 °F) and 100% humidity (left). Sealable containers suitable for the AAR-11 for storing concrete prisms (right). (RILEM, 2018c).

AAR-12: Determination of Binder Combinations for Non-reactive Mix Design or the resistance to ASR of Concrete Mixes Using Concrete Prisms – 60^{o} C (140 °F) Test Method with alkali supply

This draft test method (RILEM, 2018d) is essentially the same as RILEM method AAR-11 (RILEM, 2018c) except that the storage conditions were modified to evaluate aggregates and concrete compositions for concrete road pavements on Federal highways to avoid ASR damage, especially regarding the impact of de-icing salts and agents. It is based on a method developed by the German Road and Transportation Research Association (FGSV, 2018).

The test prisms are subjected to a pre-storage regime for a period of 28 days (Table 5); from the age of 28 days, the prisms then undergo a 14-day cycling storage regime that is repeated for a total of 10 times (Table 6) (RILEM 2018d). During the second testing period (i.e. following the 28-day pre-storage), length change measurements are taken at the end of each 14-day cycles.

It must be mentioned that this approach is still under investigation through the activities of Work Package 1 of RILEM TC-258-AAA (RILEM 2018b); consequently, changes may still be adopted before its potential adoption and publication as RILEM recommendation.

Table 5. Storage conditions prior to initial measurement at 28 days after casting (RILEM 2018d)

Step	Age of concrete (days from casting)	Duration	Storage condition
0	0-1	24 ± 1 hours	20 °C (68 °F), ≥ 90% RH, in moulds (see AAR-10 chapter 7)
1	1-7	6 days	20 °C (68 °F), in sealed test containers
2	7-21	14 days	20 °C (68 °F), 65 ± 5% RH on drying racks
3	21-27	6 days	60 °C (140 °F), over water in sealed test containers in reactor.
4	27-28	24 ± 2 hours	20 °C (68 °F), in sealed test containers

Table 6. Storage conditions during test period (14-day cycles to be repeated 10 times)

Step	**Test period (days from most recent measurement)**	**Duration**	**Storage condition**
1	0-5	5 days	60 °C (140 °F), in dryer
2	5 5-7	4 ± 1 hours 48 ± 2 hours	20 °C (68 °F), 65 ± 5% RH in closed container 20 °C (68 °F), fully immersed in test solution in sealed container (see Ch. 5.4)
3	7-13	6 days	60 °C (140 °F), over water in sealed test containers in reactor
4	13-14	24 ± 2 hours	20 °C (68 °F), in sealed test containers
5	14	-	Measure prisms. Return to step 1. Repeat the cycle of steps 1-5 ten times.

AAR-13: Application of Alkali-wrapping for Concrete Prism Testing Assessing the Expansion Potential by Alkali-Silica Reaction.

The wrapping procedure described in AAR-13 (RILEM 2018e) was originally proposed by a technical committee of the Japan Concrete Institute (JCI-TC-152A. 2017). The method aims at mitigating the effect of alkali leaching and insufficient moisture supply from/to test prisms subjected to ASR testing by wrapping the specimens with water-holding paper containing alkali solution mimicking the alkali concentration of pore solution.

At this time, no detailed procedure is available since the test procedure is still under development by the members of the Work Package 1 of RILEM TC-258-AAA. However, the following "preliminary" information can be mentioned (RILEM 2018e):

- The procedure can be used in combination with aggregate test methods (e.g. RILEM AAR-3 or AAR-4) or performance test methods for testing aggregate combinations with various binder combinations (e.g. RILEM AAR-10 or AAR-11).
- For the determination of the alkali concentration of the solution mimicking the pore solution of the concrete, a good first approximation can be obtained from the total alkali content from the binder (i.e. both Portland cement and SCMs). The alkali concentration is thus calculated and reported as [OH-] and the alkaline solution proposed for wrapping is prepared from NaOH.

- Alkali boosting can also be taken into account in the calculation of the total alkali concentration in the concrete that can be reproduced for wrapping purposes.
- The procedure will present information that will apply for testing prisms at 38°C (prisms of 75 x 75 x 250 mm (3 x 3 x 11.25 in.) and 100 x 100 x 400 mm (4 x 4 x 16 in.) size or 60 °C (140 °F) (prisms of 75 x 75 x 250 mm (3 x 3 x 11.25 in.) in size).
- For wrapping purposes, paper of natural fiber or cotton cloth were found to progressively disintegrate and are thus unsuitable. Good results were obtained with a polypropylene fiber-based paper. In order to keep the specimens from drying out, and following wrapping in the "alkaline" paper, the test prisms are wrapped in cling film.
- In the current method, the prisms are unwrapped prior to regular expansion measurements and the wrapping paper in reused.

2.2.3 Test Methods Currently Under Development

Several new non-standardized ASR test methods have been developed by different academic and government agencies. However, these new test methods have not been benchmarked to field exposure sites.

2.2.3.1 Concrete Cylinder Test Method

The concrete cylinder test (CCT) was developed to address concerns with the concrete prism test (CPT). The Texas Department of Transportation (TxDOT) and The University of Texas at Austin developed this test method in 2012, based on a concept developed by Dr. Michael Thomas at the University of New Brunswick. The test modifies the CPT by placing the concrete in a tightly secured cylinder to prevent any leaching. Preventing leaching is critical and especially for mixtures with supplementary cementing materials. A complete diagram of the concrete cylinder test (CCT) setup is shown in Figure 20 . Figure 21 presents a CCT measurement with the specimen in the comparator stand.

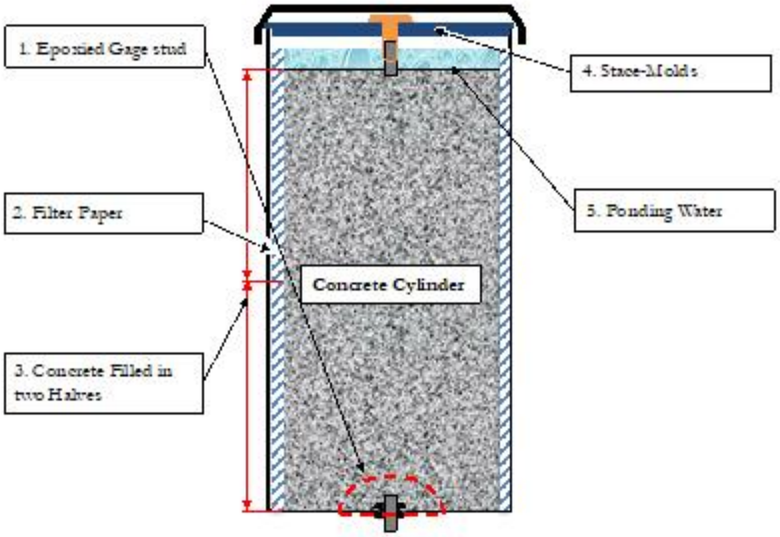


Figure 20. Diagram of CCT Setup (Stacey et al., 2016)

Figure 21. CCT during measurement (Stacey et al., 2016)

Mixture proportions are similar to the CPT, but concrete is placed into 100 x 200 mm (4 x 8 in.) plastic cylinders instead of prism molds. Gage studs are pre-placed before the concrete is introduced into the cylinders. Two filter papers line the interior of the plastic cylinder prior to the concrete placement. This filter paper distributes water throughout the cylinder and reduces the tendency for the cylinders to dry. Concrete is placed in two layers; however, the concrete that is placed in the upper half is cast 13 mm (0.5 in.) from the top of the cylinder mold (leaving a space between the concrete and the top of the cylinder). A plastic insert is placed onto the top of the cylinder with an attached gage stud that is inserted into the fresh concrete. After the cylinders are cured for 24 hours, initial expansion measurements are taken. De-ionized water is then added to the top of the cylinder and a lid is placed on the cylinder. The concrete cylinder is then placed inside a 19 L (5 gallon) bucket suspended above water similar to the CPT setup. The bucket is placed into a temperature-controlled oven at 38 ºC (100 ºF). Temperatures up to 60 ºC (100 ºF) can be evaluated in this test method. Similar to the CPT, the bucket is removed 1 day prior to measurements. If water has evaporated from the cylinder, water is added to the top of the cylinder. Currently measurements occur for up to 1 year for both aggregate reactivity and mixtures with SCMs until expansion limits can be determined.

Actual field concrete may be used in this test method. Concrete from the field may be taken and placed into this setup, and the owner may know if ASR might be of concern. With leaching being minimized, this allows for lower alkali mixtures to be tested. Based on preliminary data, the test tends to produce aggregate reactivity within 4 months and mixtures with SCMs less than 1 year. This would be of great value since the current CPT may take up to 2 years to assess mitigation options. One issue with the test method is that the water within the cylinders tends to dry out. It is important to check each cylinder once a week and fill with water if the water is low on top of the cylinder.

Data collected at TxDOT shows the effectiveness of the CCT to determine the efficacy of SCMs by gathering data with expansions greater than 0.04% at one year which was quicker than the CPT test at 2 years. Data collected at the University of Texas has shown lower alkali level mixtures expanding greater than 0.04% for mixtures that passed the CPT and have failed in exposure blocks.

2.2.3.2 University of New Brunswick Concrete Cylinder Test Method (UNBCCT)

The University of New Brunswick Concrete Cylinder Test (UNBCCT) was developed in 2015 in order to address the shortcomings of standardized ASR test methods. The primary goals of this test method were to develop a test method whereby concrete specimens are exposed to moisture; alkali leaching is prevented and the test method is capable of testing “job mixtures”. Unlike the concrete prism test (CPT, ASTM C1293), the UNBCCT consists of fabricating 145 x 280 mm (5.7 x 11 in) concrete cylinders, placing them inside a 152 x 304 mm (6 x 12 in) cylinder and filling the annulus with an artificial pore solution. Similar to the CCT (see section Concrete Cylinder Test Method), 6.3 mm (0.25 in) gauge studs are cast into the 145 x 280 mm (5.70 x 11.0 in.) concrete cylinders. Specimens are then placed inside conventional 152 x 304 mm (6 x 12 in) concrete molds where they are supported on a plastic insert to accommodate the bottom gauge pin. The annulus between the specimen and the mold is filled with a synthetic pore solution replicating the theoretical pore solution of the concrete being tested. Similar to the CPT, specimens are stored at 38 °C (100 ºF), but also at 60 °C (140 ºF) in order to accelerate the rate of expansion in an attempt to replicate expansion observed in the field. Prior to periodic measurements, specimens are removed and allowed to cool to 23 °C (73 °F**)** for 24 hours prior to conducting expansion measurements. The UNBCCT is shown to produce much higher levels of expansion compared to the conventional CPT up to approximately 500 days. The UNBCCT is also shown to result in expansion much sooner than the CPT. For example, at an alkalinity of 0.7%, the UNBCCT is shown to begin to expand after approximately 100 days compared to the CPT which begins to slightly expand after approximately 300 days. Currently, researchers at UNB are validating the test method using a range of alkali contents, various reactive coarse and fine aggregates, and SCMs.

2.2.3.3 Autoclave Expansion Test

Research during the 1980s and 1990s resulted in several ultra-rapid test methods using autoclaved mortar (Tang et al. 1983; Tamura 1987; Nishibayashi et al. 1987; Fournier et al. 1991) or concrete (Nishibayashi et al. 1996) specimens. These methods have not been standardized. In recent years, the "Laval/CANMET" mortar bar test has been the subject of renewed research interest, and a new Autoclaved Concrete Prism Test (ACPT) was developed by Giannini and Folliard (2013); these two methods will be described here.

Both the Laval/CANMET and ACPT methods were developed to have similar methodologies (specimen size, aggregate content, etc.) to current laboratory test methods for maintaining commonality. These autoclave tests are completed within one week. In addition to the short duration, differences from the standard tests involve significantly greater alkali boosting, conditioning of samples, and no intermediate expansion measurements. Figure 22 shows the mortar and concrete specimens inside an autoclave chamber.

Figure 22. Concrete prisms specimens in autoclave chamber (Giannini and Folliard, 2013)

The Laval/CANMET methodology creates a mortar similar to the AMBT; however, the alkali content of the mortar mixture is boosted to 3.5% Na_2O_{eq} by mass of the cement. Three specimens are made and cured in molds for 24 hours, demolded, and moist-cured for an additional 24 hours. An initial length measurement is taken at a temperature of 23°C (73°F), and the specimens are then autoclaved for 5 hours at 130°C (0.17 MPa gauge pressure) (266°F). The 5-hour duration refers to the hold time at the maximum temperature and pressure, and does not include the time needed to heat and pressurize the autoclave chamber, and to cool and depressurize the chamber. Specimens are removed from the autoclave after it has returned to atmospheric pressure, and are then cooled in running water down to 23°C (73°F). Once cooling is completed, a final length change measurement is taken and expansion is calculated and averaged for the three specimens. Figure 23 illustrates the experimental timeline for the test.

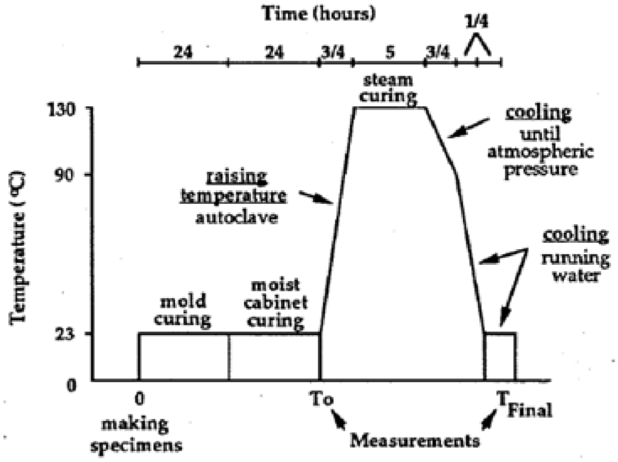


Figure 23. Schematic of Laval/CANMET procedure. For the ACPT, the steam curing period is extended to 24 hours, and cooling in water period is extended to approximately 45 – 60 minutes. (Fournier et al. 1991)

The ACPT methodology has the same grading and mixture proportions to the CPT; however, the alkali content of the mixture is boosted to 3.0% Na_2O_{eq} by mass of the cement. Three specimens are made, cured in molds for 24 hours, demolded, and moist-cured for an additional 24 hours. An initial length measurement is taken at a temperature of 23 °C (73 °F), and the specimens are then autoclaved for 24 hours at 133 °C (0.20 MPa gauge pressure). The 24-hour duration refers to the hold time at the maximum temperature and pressure, and does not include the time needed to heat and pressurize the autoclave chamber, and to cool and depressurize the chamber. Specimens are then cooled in running water to 23 °C (73 °F). Once cooling is completed, a final length change measurement is taken and expansion is calculated and averaged for the three specimens.

The primary advantage of the autoclave test methods described here is that results are obtained very quickly; including mixing and curing, three days are required for the Laval/CANMET method, and four days for the ACPT method. However, the severe test conditions (temperature, pressure, alkali loading) needed to promote expansion with known reactive aggregates in such a short period of time can create some unintended side effects, including altered pore solution chemistry, formation of abnormal hydration products, and false positive results. For example, significant expansions have been measured with otherwise non-reactive quartz sand if the autoclaving duration extends beyond 12 hours (Wood et al. 2018). Thus, the Laval/CANMET method is proposed for fine aggregates, while the ACPT is for evaluating coarse aggregate reactivity (in combination with calcareous fine aggregate only). There have also been concerns raised about the true contribution of ASR to the expansions measured in these tests, though Wood (2017) has documented the existence of ASR reaction product in autoclaved samples using

SEM/EDS. Research to investigate the applicability of these methods as performance tests of job mixes and mitigation measures is in progress.

Wood (2017) suggested the reactivity classification scheme shown in Table 7, which could be potentially incorporated into the ASTM C1778 prescriptive approach to mitigation, with limited application to lower-risk structures with design lives less than 40 years.

Table 7. Proposed aggregate reactivity for ACPT

Aggregate Reactivity Class	Description of Aggregate Reactivity	ACPT Expansion for Coarse Aggregates, %	Laval/CANMET Expansion for Fine Aggregates, %
R0	Non-reactive	< 0.09	< 0.15
R1	Moderately Reactive	≥ 0.09, < 0.12	≥ 0.15, < 0.25
R2	Highly Reactive	≥ 0.12, < 0.15	≥ 0.25, < 0.40
R3	Very Highly Reactive	≥ 0.15	≥ 0.40

The results of a multi-laboratory study on the Laval/CANMET method (Wood et al. 2017) provide significant insight into the repeatability and variability of this test, and correlation to standardized tests. Reactive vs. non-reactive classifications were in agreement with ASTM C1260 classifications for 17 of 20 aggregates, and in agreement with ASTM C1293 classifications for 10 of 10 aggregates. This is similar to what was reported by Fournier et al. (1991) in the original work on this test method. The multi-laboratory study also reported a within-laboratory coefficient of variation (CV) of 5.9% and multi-laboratory CV of 20%; both of these values are in line with the CVs reported in the ASTM C1260 and ASTM C1293 standards.

Wood (2017) also noted that the ACPT demonstrated better agreement with ASTM C1293 for classifying coarse aggregates as reactive or non-reactive than for fine aggregates. In general, fewer comparisons can be made to ASTM C1293 results because that test is not as widely-used as ASTM C1260. However, the frequent false positive and false negative results yielded by ASTM C1260 make this a less-reliable benchmark for judging new test methods.

2.2.3.4 LMC Switzerland Method

The concrete test method developed at the LMC (EPFL) is based on the Swiss standard (SIA 2042). Prisms measuring 70 x 70 x 282 mm (2.75 x 2.75 x 11.10 in) are cast using a concrete with a D_{max} equal to 22.4 mm (0.88 in), in accordance with the Swiss standard. The test modifies the standard by placing the concrete in a 100% relative humidity environment at 20°C (68°F) for 28 days (compared to only 1 day in the standard SIA version) and then places samples in simulated, matched pore solution at 60 °C (140 °F) in order to minimize leaching. Fourteen (14 days) before initial test, the amount of concrete defined by the standard is cast and six plastic bottles (55 mm (2.17 in) dia. x 89 mm (3.50 in) height) are filled. After 28 days, pore solution is extracted using the Cold Water Extraction method (CWE), which can be summarized in four main steps, as shown in Figure 24.

- Measure porosity of three first samples;
- Crush three samples and mix same amount of powder with same amount of de-ionized water 15 minutes;
- Extract solution and analyze by ICP;
- Create a simulated pore solution to match.

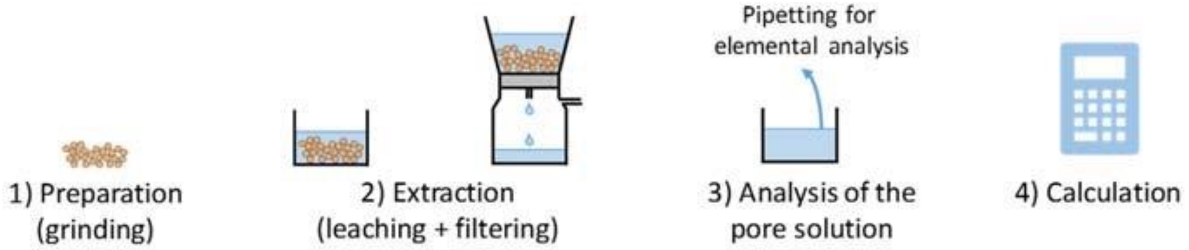


Figure 24. Cold Water Extraction for pore solution analysis

Cores taken from existing structures can tested with this method. Pore solution can be measured by CWE and a simulated, matched pore solution can be generated to store samples, while measuring expansion with time. However, the limits, in order to define if a type of concrete or mix design is reactive or not has not yet been established.

2.2.4 Summary of ASR Test Methods

Table 8 summarizes the most common standardized ASR test methods used worldwide. As described, each of these tests has its own advantages and disadvantages, but none by itself can rapidly and reliably be used to test realistic job mixtures. It is expected that the findings from this project will help to improve upon these test methods and provide calibration with long-term data from outdoor exposure sites.

Table 8. Overview of Standardized Test Methods for Aggregate Reactivity

Test method	Exposure Conditions	Specimen Description (1 in = 25.4 mm)	w/cm	Alkali Loading (% Na_2O_{eq} by mass of cement)	Failure Criteria	Pros	Cons
Accelerated Mortar Bar Test (ASTM C1260; CSA 23.2-25A; RILEM AAR-2.1)	14 days in 1N NaOH at 80 °C (176 °F)	Mortar (25 x 25 x 285 mm, 1 x 1 x 11.25 in)	0.47	No boosting; ASTM and CSA: No requirement; RILEM: Cement >1.0%.	ASTM and CSA: 0.10% at 14 days RILEM: – < 0.10%: likely non-reactive – 0.10-0.20%: potentially reactive – >0.20%: likely reactive	– Fast – Good screening test	– Must crush coarse to test – Very severe – many false positives – Must modify to detect pessimum aggregates
Accelerated Mortar Bar Test (ASTM C1567; CSA A23.2-28A; RILEM AAR-2)	14 days in 1N NaOH at 80 °C (176 °F)	Mortar (25 x 25 x 285 mm, 1 x 1 x 11.25 in)	0.47	Any cement meeting ASTM C150 (or equivalent)	ASTM and CSA: 0.10% at 14 days RILEM: – < 0.10%: likely non-reactive – 0.10-0.20%: potentially reactive – >0.20%: likely reactive	– Effective in evaluating SCMs, provided that AMBT results correlate with CPT	– Must crush coarse to test – Very severe test
Concrete Prism Test (ASTM C1293; CSA 23.2-14A; RILEM AAR-3.1)	1 year over water at 38 °C (100 °F)	Concrete (75 x 75 x 285 mm, 3 x 3 x 11.25 in)	0.42-0.45	Boost to 1.25%; ASTM and CSA: Cement 0.80 to 1.0%; RILEM: Cement 0.90 to 1.3%	ASTM and CSA: 0.04% at 1 year RILEM: 0.05 at 1 year	– Considered most reliable laboratory test	– Slow – Significant leaching – Issues detecting slow-late reacting aggregates – High interlab variability
Accelerated CPT (RILEM AAR-4.1)	13 weeks over water at 60 °C (140 °F)	Concrete (75 x 75 x 285 mm, 3 x 3 x 11.25 in)	0.42-0.45	Boost to 1.25%; Cement 0.90 to 1.3%	0.03% at 15 weeks	– Faster than standard CPT	– Leaching – Low failure criteria
Mini Concrete Prism Test (AASHTO T380)	56 days in 1N NaOH at 60 °C (140 °F)	Concrete (50 x 50 x 285 mm, 2 x 2 x 11.25 in)	0.45	Boost to 1.25%	0.04% at 56 days	– Good correlation to exposure blocks – Relatively fast	– Expansions slightly less than 1-year CPT – Expansion limit of 56 days may be better extended to 84 days for SCMs

2.3 Review of Ongoing Exposure Site Data and Field Structures

This section covers existing data from several field exposure sites that were developed for studying alkali-silica reaction (ASR) in concrete. Over 15 ASR exposure sites exist around the world, the most known are shown in Table 9. The majority of the sites exist in North America while the others are in Europe and Japan. This literature review will focus on sites in North America with an emphasis on the exposure sites at CANMET in Ottawa, Canada, The University of Texas in Austin, Texas; University of New Brunswick in Fredericton, Canada, and TxDOT in Cedar Park, Texas. The purpose of the section is to review existing literature from these sites and incorporate some unpublished data. The main objective of this literature review is to compare laboratory tests including the accelerated mortar bar test (ASTM C 1260 and C 1567) and the concrete prism test (ASTM C 1293) with outdoor exposure block data. The climate conditions for most of these sites is shown in Table 10. The Cedar Park, TX location is grouped with the Austin, TX due to proximity. Between the three sites, Austin has the highest average low and high temperature and Fredericton has the lowest average low and high temperatures.

Table 9. Worldwide exposure site locations

Exposure Site Location	**Country**	**Year Established**	**Year Demolished**	**Approx. Number of Specimens**
Treat Island, Eastport, Maine	USA	1936	-	30
British Research Establishment, BRE, Garston, England (2 sites)	Great Britain	1989 Site 1 1994 Site 2	2010 Site 1	55 Site 1 50 Site 2
Ontario Ministry of Transportation (MTO), Kingston, Ontario	Canada	1991	-	23 (ASR + ACR)
University of Toronto, Toronto and Picton Ontario	Canada	1998	-	20 (slabs in Picton, blocks in Toronto)
CANMET, Ottawa, Ontario (2 sites)	Canada	1992 2006	-	750 (total both sites)
CDC at The University of Texas, Austin, Texas (2 sites)	USA	2001 Site 1 2007 Site 2	-	300 Site 1 140 Site 2
University of New Brunswick, Fredericton, New Brunswick	Canada	2004	-	40
Mactaquac Generation Station, Fredericton, New Brunswick	Canada	2004	-	5
Shinminato Harbor, Toyama Prefecture	Japan	2004	-	20
TxDOT, Cedar Park, Texas	USA	2010	-	1300
Honolulu, Hawaii	USA	2011	-	30
Oregon State University, Corvallis, Oregon	USA	2012	-	0 - site established
PARTNER PROJECT SITES				
Valencia-Paterna	Spain	2004	-	100
Milano	Italy	2004	-	
Dusseldorf	Germany	2004	-	
Watford	United Kingdom	2004	-	
Boras and Gothenburg	Sweden	2004	-	
Boras	Sweden	2004	-	

Brevik	Norway	2004	-	
Trondheim	Norway	2004		

Table 10. Climate conditions at six exposure sites (US Climate Data, 2018)

Location	Average Low Temperature ºC (ºF)	Average High Temperature ºC (ºF)	Average Precipitation mm (in)
Austin, TX	15.0 (59.0)	26.5 (79.8)	871 (34.3)
Port Aransas, TX	22.5 (72.5)	25.5 (77.9)	884 (34.8)
Corvallis, OR	5.5 (41.9)	17.4 (63.4)	1088 (42.8)
Newport, OR	6.7 (44.1)	14.7 (58.5)	1768 (69.6)
Fredericton, NB (CA)	-0.6 (30.9)	11.0 (51.9)	1100 (43.3)
Treat Island, ME	1.8 (35.3)	11.4 (52.6)	1140 (44.9)
Honolulu, HI	21.5 (70.7)	29.1 (84.5)	434 (17.1)
Lawrence, MA	10.1 (50.2)	15.4 (59.8)	1310 (51.6)

In general, the sites in Texas, Ottawa and New Brunswick contain a significant number of exposure blocks that are of the same size and are measured in a nearly identical way. The number of roughly the same size blocks is contained in the table below. In addition, each site has investigated different size specimens specific to different research projects or regional needs. Those include slabs, both elevated, on grade and partially submerged in soil, scaled columns and scaled bridge deck representative elements. For the purposes of comparison this report will only focus on the blocks that are 394 x 394 x 762 mm (15.5 x 15.5 x 30 in).

Table 11 provides the number of exposure blocks at located each exposure site. Over 2000 exposure blocks exist between all sites. The majority of the exposure blocks at CANMET, UNB and UT Austin contain a high alkali cement content while the TxDOT site contains a variety of alkali levels.

Table 11. Exposure block sites and number of blocks

Site	# of Blocks
CANMET, Ottawa, ON, CA	750
UNB, Fredericton New Brunswick, CA	40
UT Austin, Austin, TX, USA	440
TxDOT, Cedar Park, TX, USA	1300

Prior to reviewing the exposure blocks at each site, Figure 25 compares exposure block data for the two different aggregates at the three exposure sites and how the climatic conditions play a role on exposure sites (Drimalas et al. 2012). These exposure blocks are boosted and do not contain any SCMs. In all cases, the exposure blocks in Texas expanded at earlier times and have the highest ultimate expansion. This is mainly due to the higher temperature and the longer duration of warmer temperatures in Texas compared to Canada. These comparisons show how climatic conditions can dramatically change the performance of an aggregate.

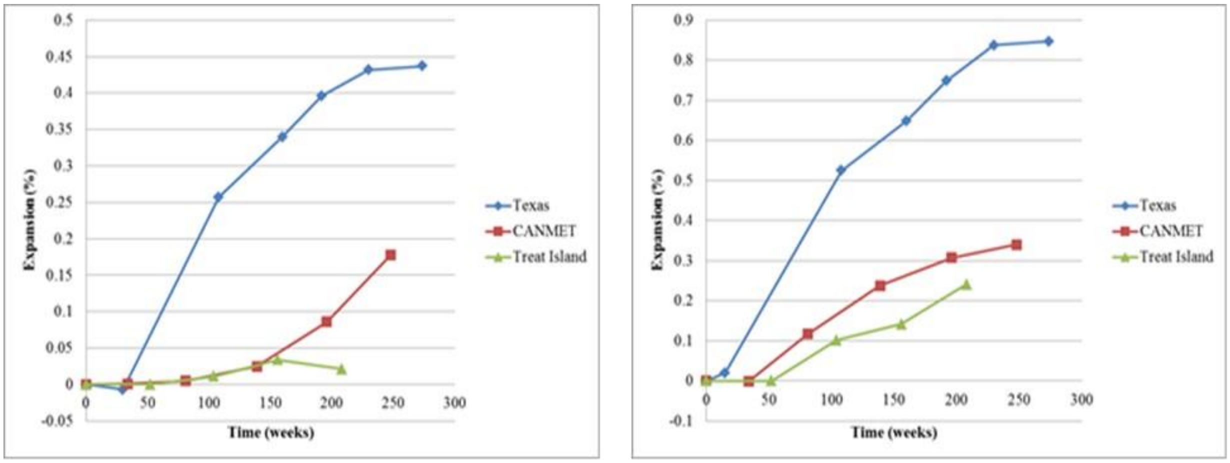


Figure 25. Expansion values of ID (left graph) and JB (right graph) aggregate exposure blocks at the three different exposure sites (Drimalas et al. 2012)

2.3.1 CANMET Outdoor Exposure Site

In 1991, CANMET began a research program for comparing laboratory tests to field exposure blocks. This site is located in Ottawa, Canada. This site contains over 650 exposure blocks evaluating over 15 aggregates, low and high alkali cements, SCMs (fly ashes and grand granulated slag), and lithium admixtures. The aim of the study is to evaluate the potential of alkali-reactivity of aggregates and the efficacy of SCMs for preventing ASR. Accelerated mortar bar tests (ASTM C1260 and ASTM C1567) and the accelerated concrete prism tests (ASTM 1293) are the three test methods that are used in comparing to field exposure blocks.

One of the CANMET studies focuses on concrete exposure blocks cast with the highly reactive Spratt aggregate and the moderately reactive Sudbury aggregate. Mixtures for each aggregate consisted of a low alkali cement, high alkali cement, and mixture combinations of fly ash, silica fume, and slag replacing the high alkali cement. Figure 26 shows the 20-year exposure block data along with AMBT and CPT data. An unboosted (no additional alkalis), boosted (+) and double boosted (++) exposure block were cast for each SCM combination. After 20 years, it was determined that the efficacy of SCMs varied and that the concrete prism test was reliable in predicting exposure blocks with SCMs at 10 years but was not as accurate at 20 years (Fournier et al. 2018).

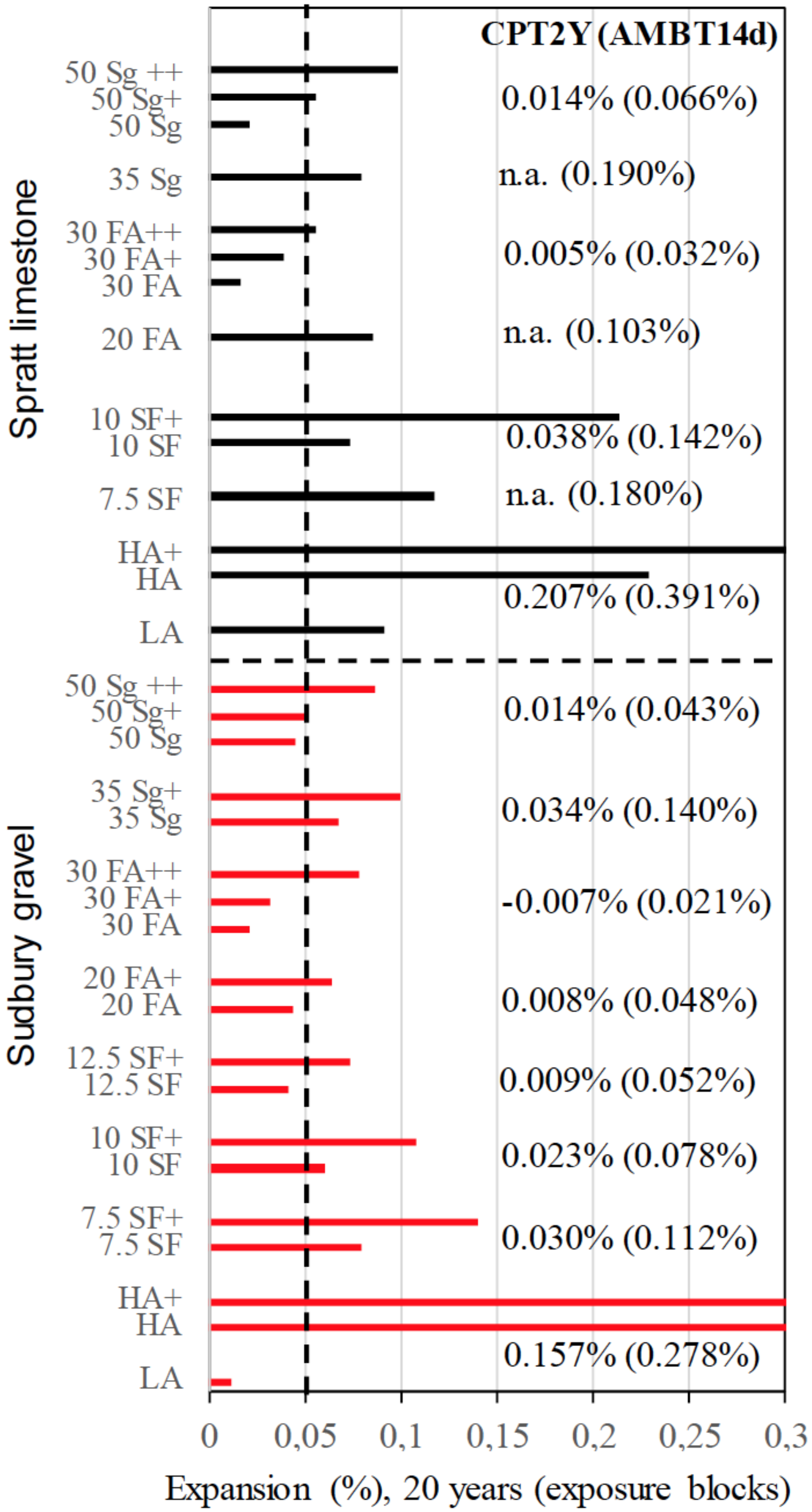


Figure 26. Spratt and Sudbury exposure block expansions data with SCMs compared to CPT and AMBT.

Another CANMET study compares exposure blocks that are unboosted with SCMs is shown in Figure 27 (Fournier et al., 2016). This study focuses on 8 aggregates with exposure blocks at an age of 10 and 15 years. For each aggregate, a control block along with 20 and 30% Class F mixtures are shown. The mixtures with highly reactive aggregates are not mitigated after 10 and 15 years of exposure. This is a limited series of exposure blocks show that unboosted exposure blocks that were able to pass the CPT and AMBT do show failure in outdoor exposure blocks in highly reactive aggregates.

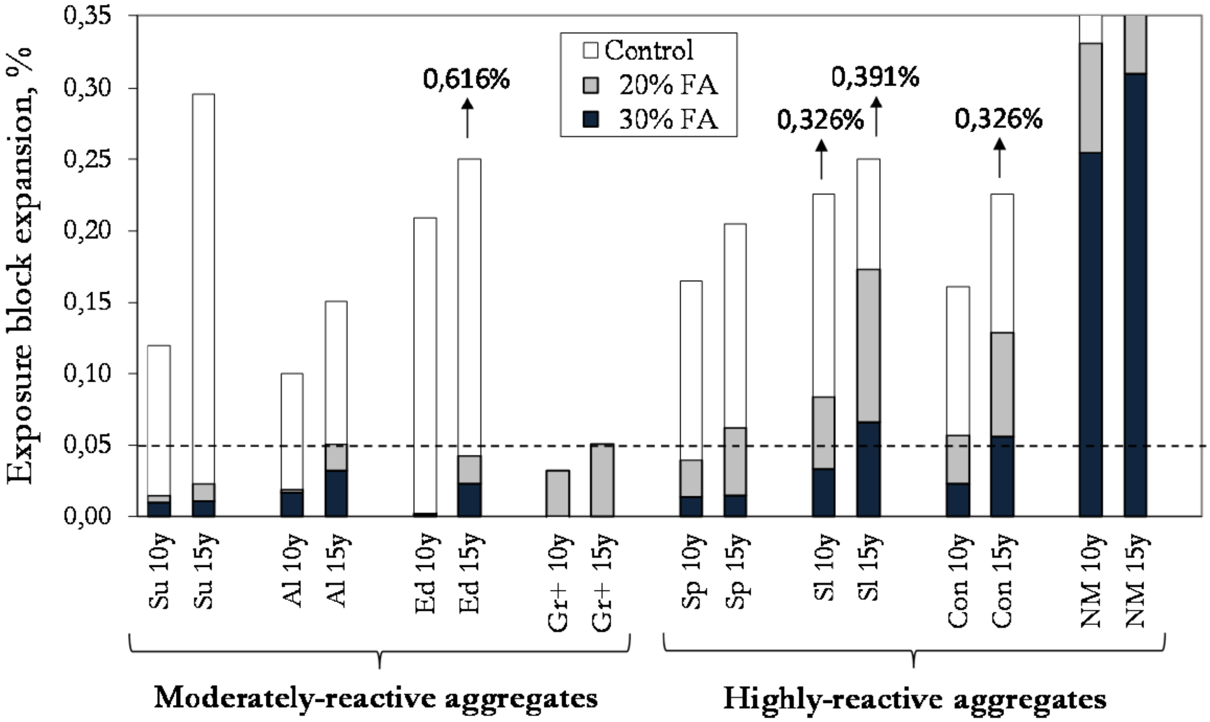


Figure 27. Unboosted exposure blocks with and without SCMs at 10 and 15 years

Another CANMET series of aggregates shown in Figure 28 (Fournier et al., 2016) shows that exposure blocks after 5 years and 10 years begin to fail with Class F ash up to 30% replacement for a moderate reactive aggregate. In addition, ternary blends with Class F fly ash show expansion of exposure blocks expanding after 5 and 10 years of exposure. The lithium dosage isn't at the recommended dosage but even with 50 or 75% of the recommended lithium dosage, the ternary blend of lithium and Class F fly ash does not mitigate.

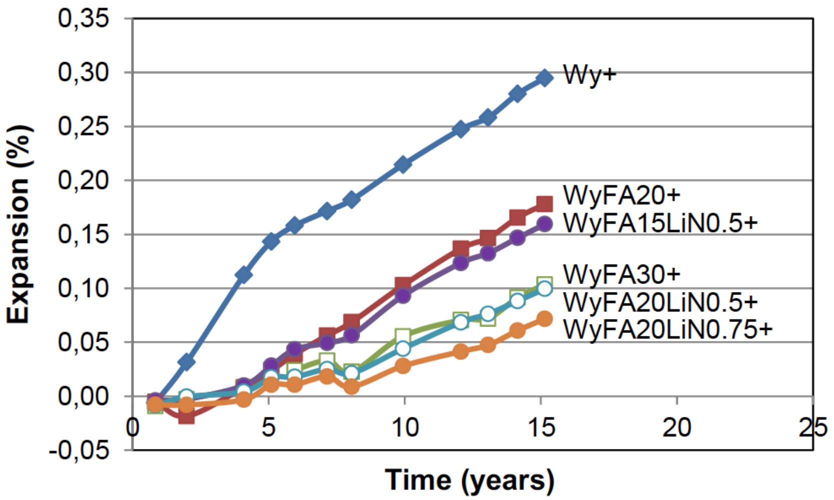


Figure 28. Exposure blocks expansions with a moderate reactive aggregate with Class F Fly ash and ternary blends of class f fly ash and lithium

2.3.2 University of Texas at Austin Outdoor Exposure Site

The University of Texas at Austin exposure site was developed in 2001 and includes over 400 concrete exposure blocks that focuses on linking laboratory testing to field performance (Folliard et al., 2006). In addition to evaluating alkali-silica reaction (ASR), some exposure blocks were heat-treated to diagnose delayed ettringite formation (DEF). This comparative field and laboratory test program was initiated for the Texas Department of Transportation (TxDOT) to evaluate aggregates within the state of Texas and now it involves exposure blocks for several agencies around the world.

This site contains exposure blocks that were manufactured with over 35 reactive aggregates from various locations in the U.S.A., Canada, and Europe. Table 12 provides the details of the 20 reactive coarse aggregates and 15 reactive fine aggregates used in this testing program carried out at the University of Texas at Austin. When the fine aggregates were tested in concrete they were combined with a non-reactive quarried limestone (C6 in Table 12), and when the coarse aggregates were tested they were combined with non-reactive sand manufactured from the same limestone (F6 in Table 12).

Low and high alkali cements have been used to produce exposure block concrete mixtures. A variety of supplementary cementing materials (SCM) have been used in the program. The majority of concrete mixtures have a total cementitious materials content of 420 kg/m^3 (708 lb/yd^3) required by ASTM C1293. The coarse-to-fine aggregate ratio for the concrete was 70:30 by volume, which is also a requirement of ASTM C1293. The w/cm was held constant at 0.42 for all admixtures, and water reducers were added for mixtures that had a slump of less than 50 mm (2 in.). The majority of the concrete mixtures have their alkali content boosted to 1.25% Na_2O_{eq} (by cement mass) by adding sodium hydroxide to the mixing water.

Figure 29 through Figure 36 summarize the overall findings from the Austin exposure site. All of the reactive coarse and fine aggregates tested at the University of Texas at Austin exposure site have shown to expand with alkalis boosted to 1.25% Na_2O_{eq} except for the non-reactives (C6 and F6).

Figure 29 and Figure 30 shows the expansions of reactive coarse and reactive fine aggregates, respectively. The rates and ultimate expansions have shown to vary significantly for the different types of aggregate mineralogy. Several of the coarse aggregates show a continuous expansion while most of the fine aggregates show a flat-line in ultimate expansion. It is also noticeable that the fine aggregates show a higher ultimate expansion compared to coarse aggregates. These same aggregates were also evaluated at lower alkali contents of 4.18 kg/m^3 (6.7 lb/yd^3).

Figure 31 and Figure 32 show the unboosted exposure block expansions of reactive coarse and reactive fine aggregates, respectively. Three coarse aggregates did not expand at this lower alkali content. However, all of the other aggregates still expand at high levels.

The results obtained on blocks stored on the University of Texas at Austin exposure site were used to confirm accelerated laboratory tests. The results are compared to the Concrete Prism Test (ASTM C 1293) and Accelerated Mortar Bar Test (ASTM C 1260) regarding the reactivity potential of the aggregates tested. Figure 33 shows a stronger correlation between ASTM C1293 and exposure block expansion compared to ASTM C1260 (Figure 34) and the same exposure blocks.

The majority of exposure blocks that contain SCMs at the UT Austin exposure site are boosted to 1.25% alkalis based on the cement. Mixtures include Class F fly ash, Class C fly ash, slag, silica fume, ternary blends, and lithium nitrate admixtures. Figure 35 and Figure 36 shows the relationship between the accelerated laboratory tests and boosted exposure blocks with SCMs. For both accelerated laboratory tests, there is a poor correlation between lab and field results.

Table 12. Aggregates evaluated at UT Austin exposure site

Aggregate	ID	Mineralogy Source	Location
Coarse	C1	Chert and quartzite	Eagle Lake, TX
	C2	Tan dolomite carbonate	Eagle Pass, TX
	C3	Limestone	Elgin, OK
	C4	Limestone	Helotes, TX
	C5	Mixed quartz/chert	Ashtown, AR
	C6	Limestone	San Antonio, TX
	C7	Limestone	Ontario, Canada
	C8	Mixed mineralogy gravel	Ontario, Canada
	C9	Chert with quartz and limestone	Victoria, TX
	C10	Rhyolitic volcanic rocks with quartz and granite	Albuquerque, NM
	C11	Mixtures of granodiorite and metadacite	North East, MD
	C12	Quartzite	Dell Rapids, SD
	C13	Quartzite	New Ulm, MN
	C14	Granite and Quartzite Gravel	Cheyenne, WY
	C15	Ryholite/Mixed Quartz	Rockville, VA
	C16	Granitic gneiss, metarhyolite	North Garden, VA
	C17	Greywacke	Moscow, PA
	C18	Volcanic	Idaho
	C19	Quartzite Gravel	Waco, TX
	C20	Limestone	Comal County, TX
Fine	F1	Mixed quartz/chert/feldspar sand	El Paso, TX
	F2	Mixed quartz/chert sand	Mission, TX
	F3	Quartz sand	Cleveland, TX
	F4	Quartz	Austin, TX
	F5	Quartz	Amarillo, TX
	F6	Manufactured limestone sand	San Antonio, TX
	F7	Mixed quartz/chert sand	Robstown, TX
	F8	Siliceous Sand	Omaha, NB
	F9	Quartz	Austin, TX
	F10	Quartz	Austin, TX
	F11	Quartz	
	F12	Quartz	Bastrop, TX
	F13	Quartz	Eagle Pass, TX
	F14	Quartz	
	F15	Quartz	Yarrington, TX

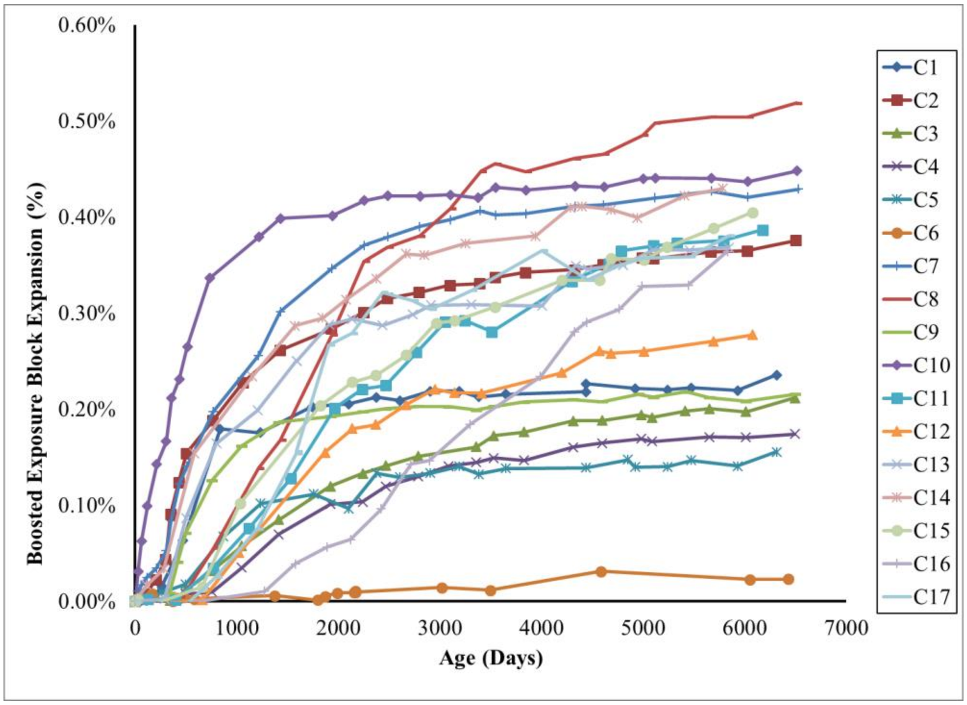


Figure 29. Long-term exposure block expansions of alkali-reactive coarse aggregates with no SCMs that are boosted to 1.25% Na_2O_{eq}

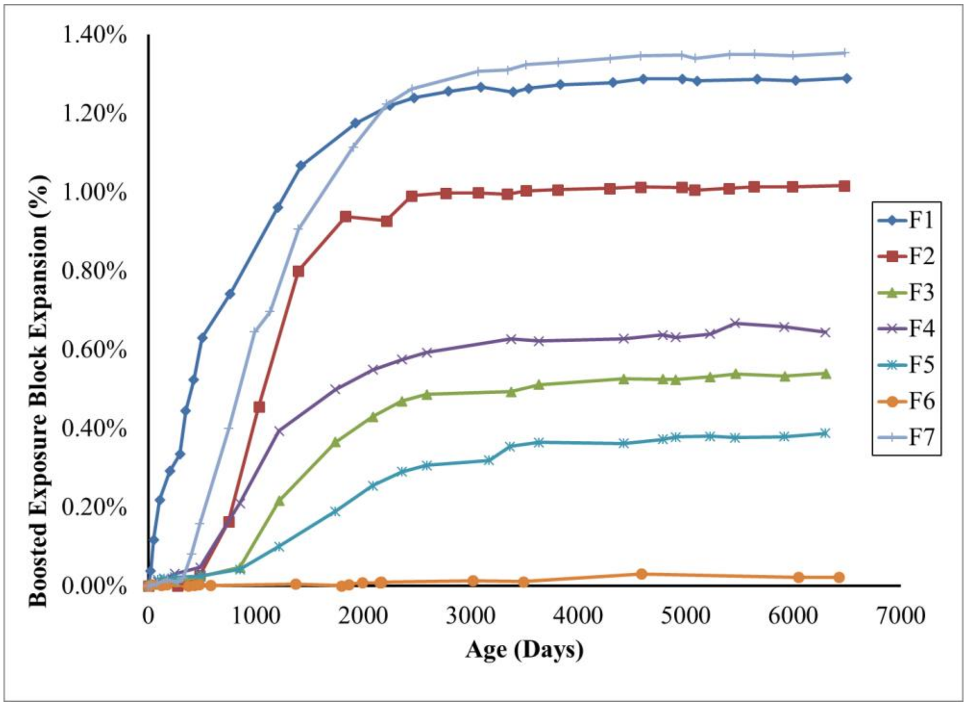


Figure 30. Long-term exposure block expansion of alkali-reactive fine aggregates with no SCMs boosted to 1.25% Na_2O_{eq}

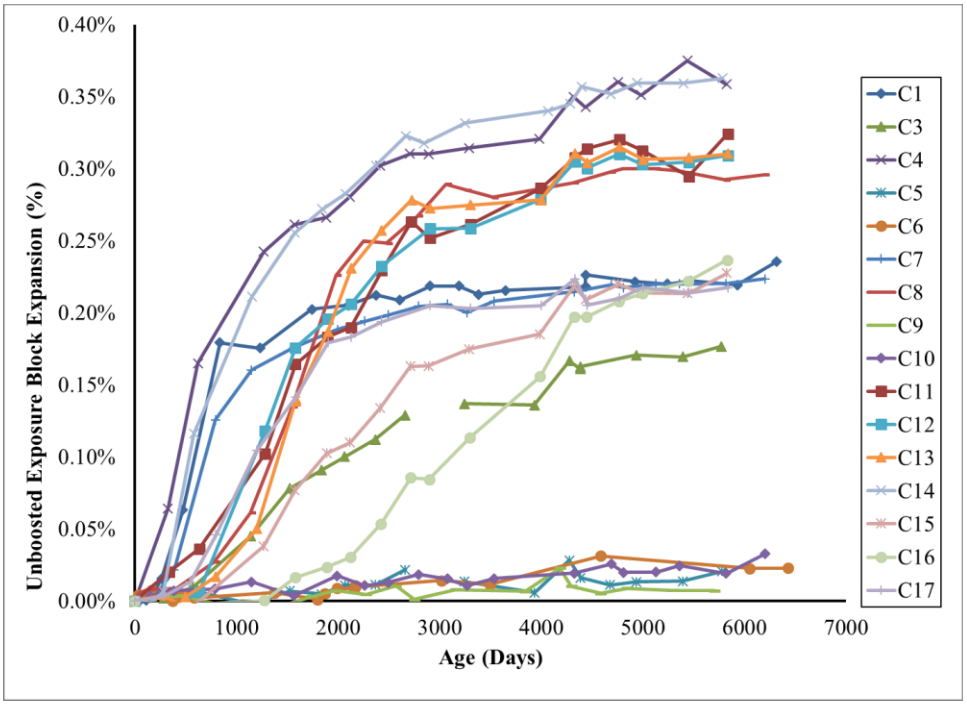


Figure 31. Long-term exposure block expansion of alkali-reactive coarse aggregates with no SCMs using 0.95% Na_2O_{eq} cement

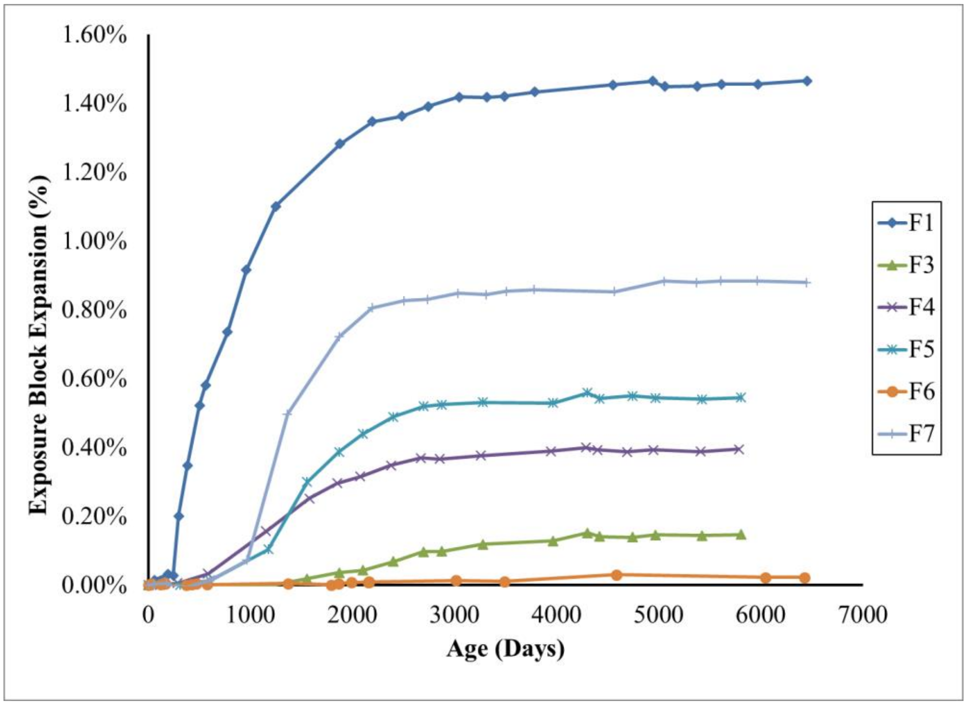


Figure 32. Long-term exposure block expansions of alkali-reactive fine aggregates with no SCMs using 0.95% Na_2O_{eq} cement

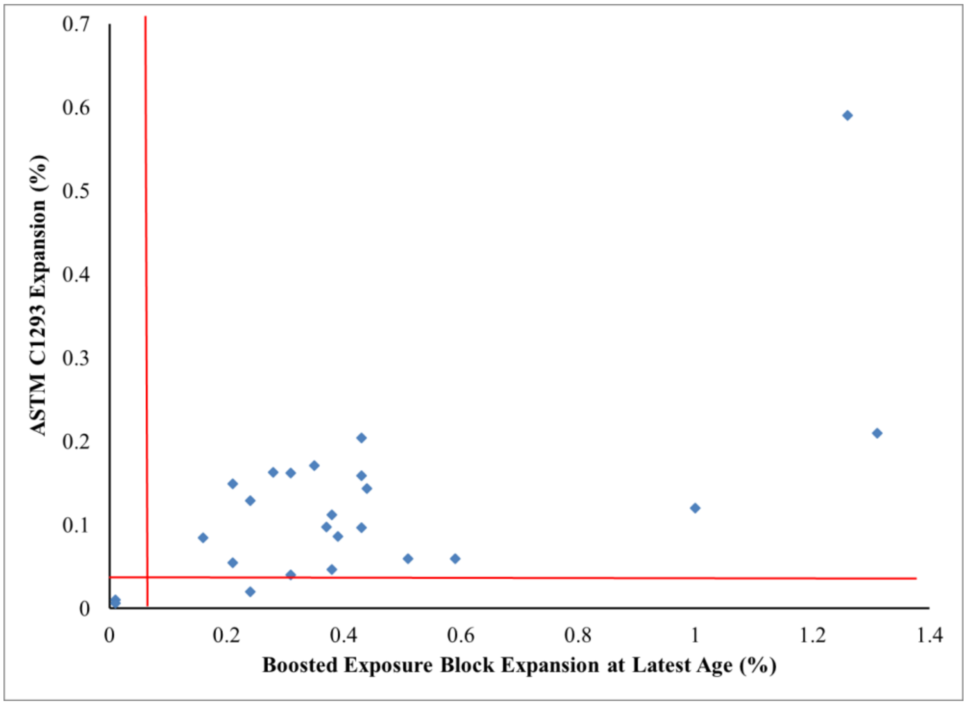


Figure 33. Comparison of ASTM C1293 and expansions from boosted exposure blocks

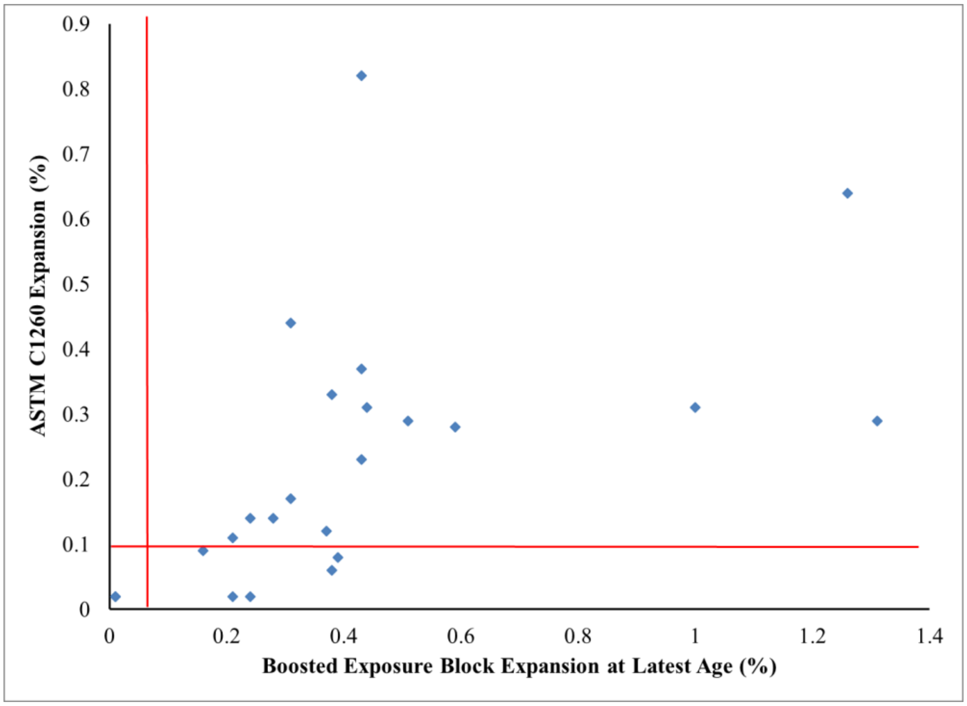


Figure 34. Comparison of ASTM C1260 and expansions from boosted exposure blocks

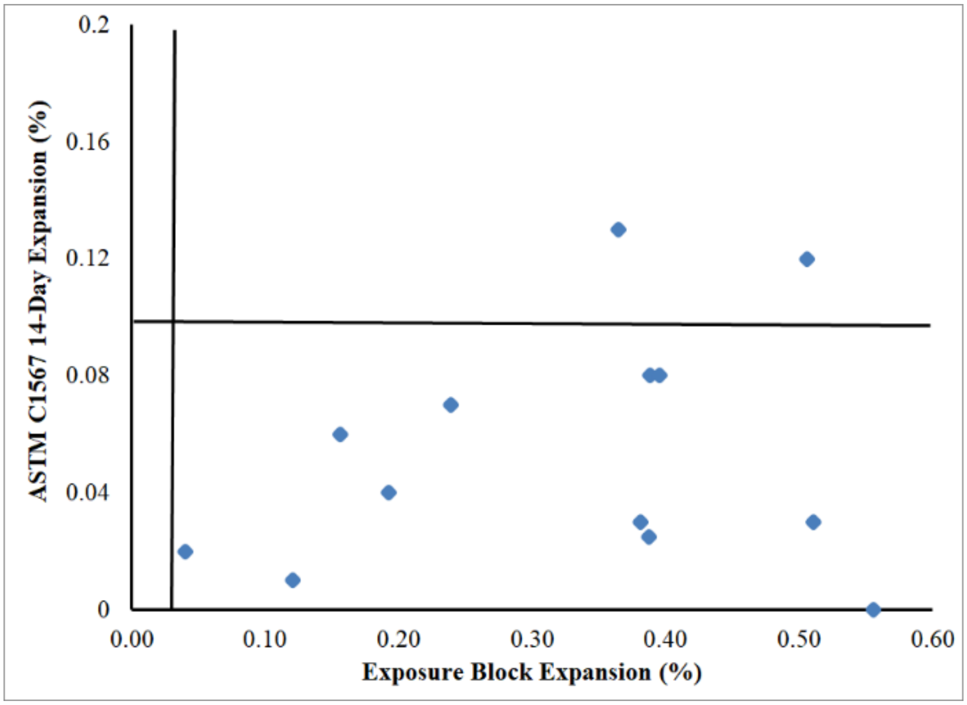


Figure 35. Comparison of ASTM C1567 and expansions from boosted exposure blocks that contain SCMs

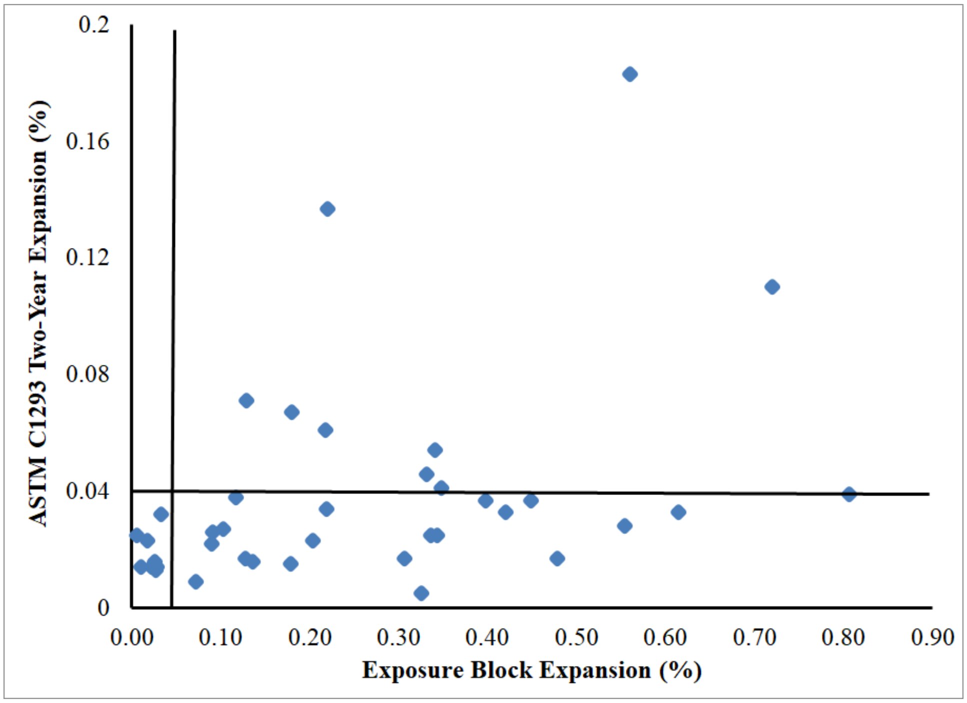


Figure 36. Comparison of ASTM C1293 and expansions from boosted exposure blocks that contain SCMs

2.3.3 University of New Brunswick Outdoor Exposure Site

In 2005 an exposure site was constructed at the University of New Brunswick (UNB). The main incentive for constructing the site at that time was to evaluate a range of preventive measures for controlling damaging reaction with the aggregate used for construction of the Mactaquac Dam in 1968 as in 2005 it was intended to replace these structures using the same reactive aggregate (Hayman et al. 2008). There are approximately 40 blocks on this site constructed with this aggregate and various preventive measures including low concrete alkali content, Class F and C fly ash, silica fume, slag, and lithium. In 2020 most of these blocks will reach an age of 15 years and, at that time, the data will be analyzed and reported for use in this project.

2.3.4 TxDOT Outdoor Exposure Site

The Texas Department of Transportation (TxDOT) exposure site is located in Cedar Park, Texas. This site is 10 miles from the University of Texas at Austin exposure site. The site was established in 2010 and contains 1400 exposure blocks that evaluate multiple concrete deterioration mechanisms including alkali-silica reaction and delayed ettringite formation. A large portion of the exposure site evaluates mixtures containing low w/cm and their admixture compatibility. The majority of the exposure blocks have dimensions of 380 x 380 x 380 mm (15 x 15 x 15 in) and a smaller subset of blocks are 380 x 380 x 720 mm (15 x 15 x 30 in).

A wide selection of materials were obtained to cast the TxDOT exposure blocks in Cedar Park, TX. Including 28 coarse aggregate sources, 47 fine aggregate sources, 37 cements and 31 admixtures. The majority of aggregates are sourced from Texas. Cement contents vary from 385 to 867lb/yd^3 with w/cm ranges of 0.25 to 0.45. The majority of the blocks mimicked precast mixtures. These precast mixtures had low w/cm and high cement contents.

On August 2, 2019, the research team visited the TxDOT exposure site to evaluate exposure blocks that had alkali loadings between 1.5 and 2.1 kg/m^3 (2.5 and 3.5 lb/yd^3) and contained SCMs. The research team did find some cracking occurring on the exposure blocks; however, it is not certain if this crazing and cracking is due to ASR or some other form of cracking. Figure 37. Photo of TxDOT exposure block 64 with hairline cracks on top and extending into the side of the block. This other form of cracking may be due to 1) shrinkage cracking and 2) overdosage of superplastizer which created a very fluid mixing that led to early age cracking on the surface. With the aggregates having low reactivity and with an overall low alkali loading, it is a low possibility that ASR is occurring in these exposure blocks. Cracks associated with ASR will show this crack from top to side of the exposure block. However, this block also seems to be overdosed with superplasticizer. Future forensic work (petrographic examination) may be done on a few of the exposure blocks to confirm if ASR is occurring. Table 13 summarizes the details of the blocks evaluated, including any appearance of cracks. These exposure blocks are of high importance to the ASR community. As they are some of the only exposure blocks that contain low and moderate alkali levels and contain SCMs.

Figure 37. Photo of TxDOT exposure block 64 with hairline cracks on top and extending into the side of the block

Table 13. Observations of TxDOT Exposure Blocks

Block #	Cast Date	Coarse Aggregate Reactivity	Fine Aggregate Reactivity	w/cm	SCM Amount	Cement Content (lb/yd^3)*	Alkali Loading (lb/yd^3)*	Observation
52	3/16/2011	R0	R1	0.33	2	609	3.0	No Cracking
54	3/16/2011	R0	R1	0.33	25	547	2.5	No Cracking
55	3/17/2011	R0	R1	0.33	25	617	3.0	No Cracking
56	3/17/2011	R0	R1	0.33	25	712	3.5	No Cracking
57	3/28/2011	R0	R1	0.45	2	511	2.5	slight crazing
58	3/28/2011	R0	R1	0.45	2	604	3.0	minor surface cracking
59	3/29/2011	R0	R1	0.45	2	750	3.5	minor surface cracking
62	3/29/2011	R0	R1	0.45	25	530	2.5	minor surface cracking
63	3/29/2011	R0	R1	0.45	25	634	3.0	hairline crack
64	3/29/2011	R0	R1	0.45	25	747	3.5	minor visible cracking
73	9/12/2011	R1	R1	0.45	25	576	2.5	minor hairline crack
74	9/12/2011	R1	R1	0.45	25	681	3.0	No Cracking
83	9/28/2011	R1	R1	0.33	25	558	2.5	No Cracking
84	9/28/2011	R1	R1	0.33	25	670	3.0	No Cracking
130	8/16/2011	R1	R1	0.33	25	528	2.5	No Cracking
131	8/16/2011	R1	R1	0.33	25	665	3.0	good/side crazing
132	8/9/2011	R1	R1	0.33	25	792	3.5	good/side crazing
133	7/27/2011	R1	R1	0.45	25	568	2.5	surface crazing
134	8/9/2011	R1	R1	0.45	25	632	3.0	hairline crack
135	8/12/2011	R1	R1	0.33	25	813	3.5	good/slight side crazing
142	7/25/2011	R1	R1	0.33	25	506	2.5	No Cracking
143	7/27/2011	R1	R1	0.33	25	613	3.0	No Cracking
144	7/20/2011	R1	R1	0.33	25	700	3.5	No Cracking
145	7/21/2011	R1	R1	0.45	25	518	2.5	No Cracking
146	7/22/2011	R1	R1	0.45	25	594	3.0	No Cracking
147	7/27/2011	R1	R1	0.45	25	721	3.5	minor crazing
201	7/8/2011	R1	R1	0.33	25	606	2.5	minor side cracking
202	7/8/2011	R1	R1	0.33	25	728	3.0	surface crazing
203	7/11/2011	R1	R1	0.45	25	606	2.5	surface crazing
220	6/15/2011	R0	R1	0.33	25	586	2.5	minor side crazing
221	6/15/2011	R0	R1	0.33	25	703	3.0	minor side crazing
222	6/15/2011	R0	R1	0.33	25	820	3.5	crazing/hairline crack
226	6/17/2011	R0	R1	0.45	25	567	2.5	crazing/hairline crack
227	6/17/2011	R0	R1	0.45	25	680	3.0	hairline surface crack
228	6/17/2011	R0	R1	0.45	25	794	3.5	crazing/hairline crack
303	6/17/2011	R0	R1	0.45	25	519	2.5	hairline surface crack
304	6/17/2011	R0	R1	0.45	25	627	3.0	hairline surface crack
305	6/17/2011	R0	R1	0.45	25	726	3.5	hairline cracks
480	10/3/2011	R1	R1	0.33	25	789	3.5	hairline crack

** 1 lb/yd^3 = 0.59 kg/m^3*

2.4 Review of Guidance Documents

2.4.1 *Current Guidance in North America*

In North America there is generally strong uniform guidance at the national level on how to evaluate aggregate reactivity and to select preventive measures following either a performance- or prescriptive-based approach. The model approach for North America has been a suite of standards from the Canadian Standards Association (CSA). Close collaboration between Canadian and US researchers has further refined these standards and informed each other's approaches of modifications the other country is considering. Further, several federally-funded research projects in the US solidified a unified approach. Between FHWA, ASTM, AASHTO and CSA the general approach to identifying potential alkali-aggregate reactivity is shown from the ASTM C1778 guidance document, Figure 38, which is germane to this project. It should be noted that in all national-level North American Standards, if potential alkali-carbonate reactivity is identified that aggregate should be avoided for use in portland cement concrete. It certainly can have a home in other applications such as asphalt, trap rock, base fill, etc.

Once the potential for reactivity is known three general approaches are possible to proceed for concrete construction:

1. If the aggregate is deemed non-reactive it can be used without preventive measures in concrete construction.
2. If the aggregate is deemed potentially alkali-silica reactive it can be used following either a prescriptive approach or a performance-based approach for reducing the risk of deleterious alkali-silica reaction.
3. If the aggregate is deemed potentially alkali-carbonate reactive it should not be used in portland cement concrete construction.

In item 2 above there is a very important point to highlight – ***preventive measures such as supplementary cementitious materials, lowering alkali loading, use of lithium nitrate, etc. only reduce the risk of deleterious alkali-silica reaction***. In no document in North America is a guarantee given that alkali-silica reaction can be completely avoided. Increasing the replacement of SCMs, using ternary blends, and lowering alkali content – all in harmony give the best combination for avoiding alkali-silica reaction. Certainly, having SCMs present generally reduces damage that would occur from using the aggregate solely on its own without any preventive measure. In the ***prescriptive approach*** the exposure environment, level of risk of having ASR, aggregate reactivity and structural classification are taken into account to try and address this issue – reducing the risk of ASR to a level appropriate for the structure. For the ***performance-based approach*** testing generally following ASTM C1567/C1293 for mitigation efficiency evaluation is done. In the performance-based approach the acceptable risk of ASR occurring, e.g. taking into account exposure conditions, structural importance, etc. is not taken into account. The user relies on combinations of materials that pass (e.g. fall below the expansion limit in the respective test), to determine if the mixture will not exhibit deleterious reaction due to ASR. ***This is an inherent challenge in these standards currently and an area that merits attention in the future with projects such as the one herein.***

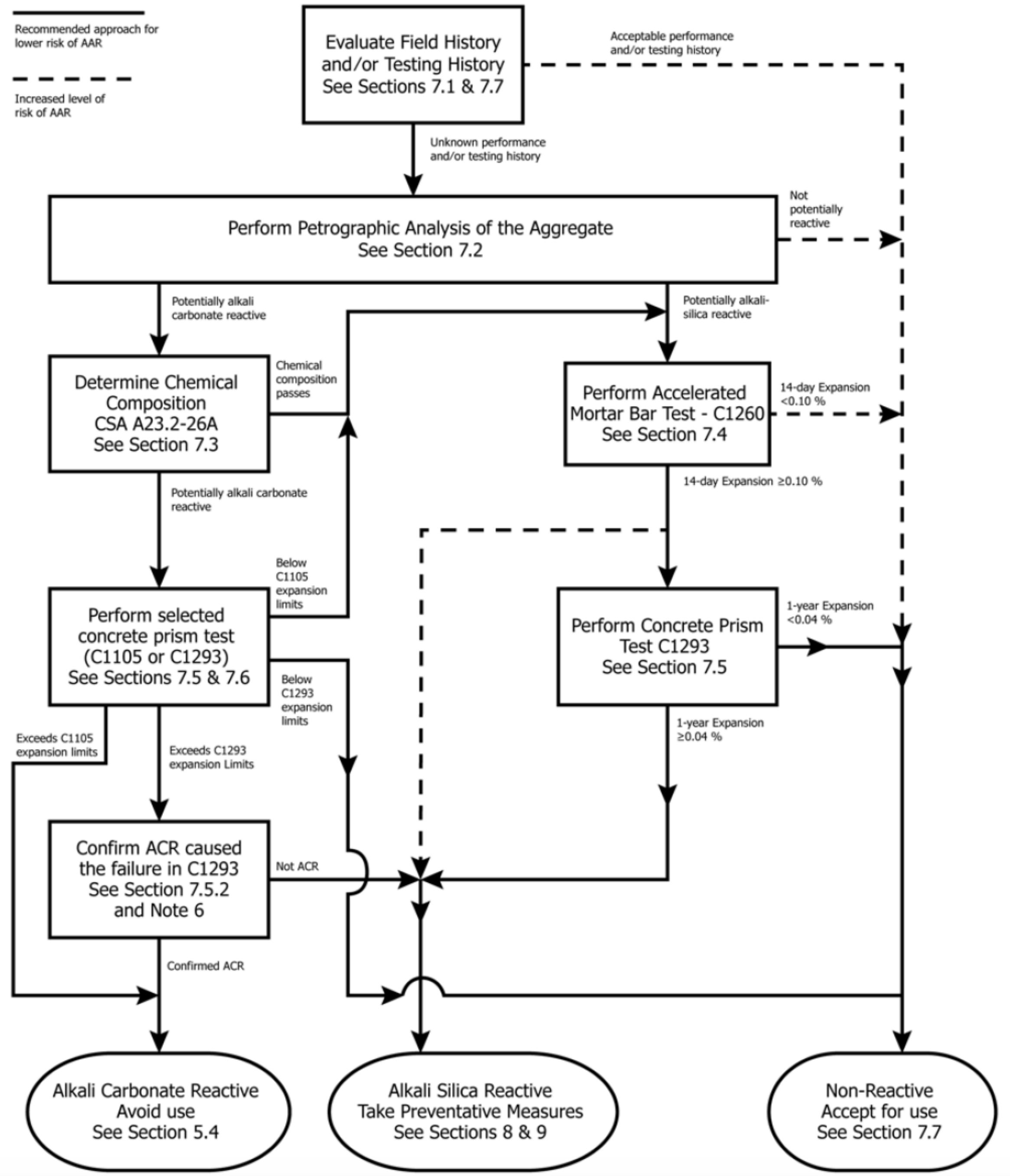


Figure 38. Figure indicating the general approach for testing and evaluating the potential for alkali-aggregate reactivity (after ASTM C1778-19A)

In Canada, this generally uniform approach continues through to the provincial and local governments. However, in the US this can vary widely at the state level which will be highlighted later in this section. In the following section some of the differences in the specific standards/guidance documents is highlighted to provide a high-level overview of the documents. More attention is given to ASTM C1778 and AASHTO R80 since they are the main documents under study in this project.

2.4.1.1 ASTM C1778

ASTM C1778-19a "Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete" is a standard developed based on a call from industry to have uniform guidance within ASTM regarding the interpretation of standard ASR-related test methods and then to selection appropriate mitigation methods to reduce the risk of deleterious expansion. This document has received significant attention since its inception in 2014 and has since seen revisions in 2016, 2019 and 2019a. Much of the revisions have revolved around clarifying the flow chart in Figure 1, providing clarifying language regarding what constitutes adequate field history for an aggregate source and defining alkali loading to differentiate the alkali loading in concrete from the alkali content of the portland cement. Current efforts within the ASTM C09.50 Subcommittee on Aggregate Reactions in Concrete are centered on how to include natural pozzolans or ground glass in the standard and work to try and clarify different levels of prevention within the performance-based approach.

2.4.1.2 AASHTO R80

AASHTO R80-17 "Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction" is very similar to ASTM C 1778 and has also been through several revisions since its initial inception as AASHTO PP-65, becoming AASHTO R80-16 and then -17. One of the most significant difference between AASHTO R80 and the ASTM C1778 is that AASHTO R80 provides an approach for assessing the efficacy of lithium nitrate to prevent ASR in the accelerated mortar bar test (AMBT). However, ASTM C1778 does not provide this information for the AMBT. The reason is that C1778 refers to approved test methods within ASTM (or sometimes CSA) for inclusion in the guide. ASTM and CSA are consensus standards whereas AASHTO standards are not. Currently, there is no standard ASTM or CSA test method for assessing the efficacy of lithium nitrate in the accelerated mortar bar method. It may be assessed in the concrete prism test (2-year).

2.4.1.3 FHWA

In 2008 Thomas et al. published "Report on Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction" as part of an FHWA-funded research project. This report was the foundation for what eventually became AASHTO R80 and ASTM C1778. Modifications have been made to the language from the report to develop standards language specific to AASHTO R80 and ASTM C1778 but the essence of the recommendations in that report are reflected in the two afore-mentioned standards.

2.4.1.4 CSA A23.2-27a

A23.2-27A "Standard Practice to Identify Degree of Alkali-Reactivity of Aggregates and to Identify Measures to Avoid Deleterious Expansion in Concrete". This is the oldest standard focused on identifying alkali-aggregate reactivity and providing pathways to follow a prescriptive or performance-based approach for avoiding deleterious expansion in concrete. It does differ slightly from ASTM C1778 or AASHTO R80 in several areas. The limits for the concrete prism test are 0.040% which has one more significant digit than ASTM C1778 but is the same as AASHTO R80. The expansion limit in the accelerated mortar bar test is 0.150% which is higher than both ASTM C1778 and AASHTO R80. In this standard when using performance history to qualify an aggregate source's reactivity it recommends that the structure be at least 10 years old whereas ASTM C1778 states that structures should be at least 15 years old. AASHTO R80 states "structures should be at least 10 years old and preferably more than 15 years old as deleterious expansion due to AAR can take more than 10 years to develop." This standard provides a more detailed flow chart than ASTM C1778 or R80 for determining aggregate reactivity and selecting preventive measures, as shown in Figure 39.

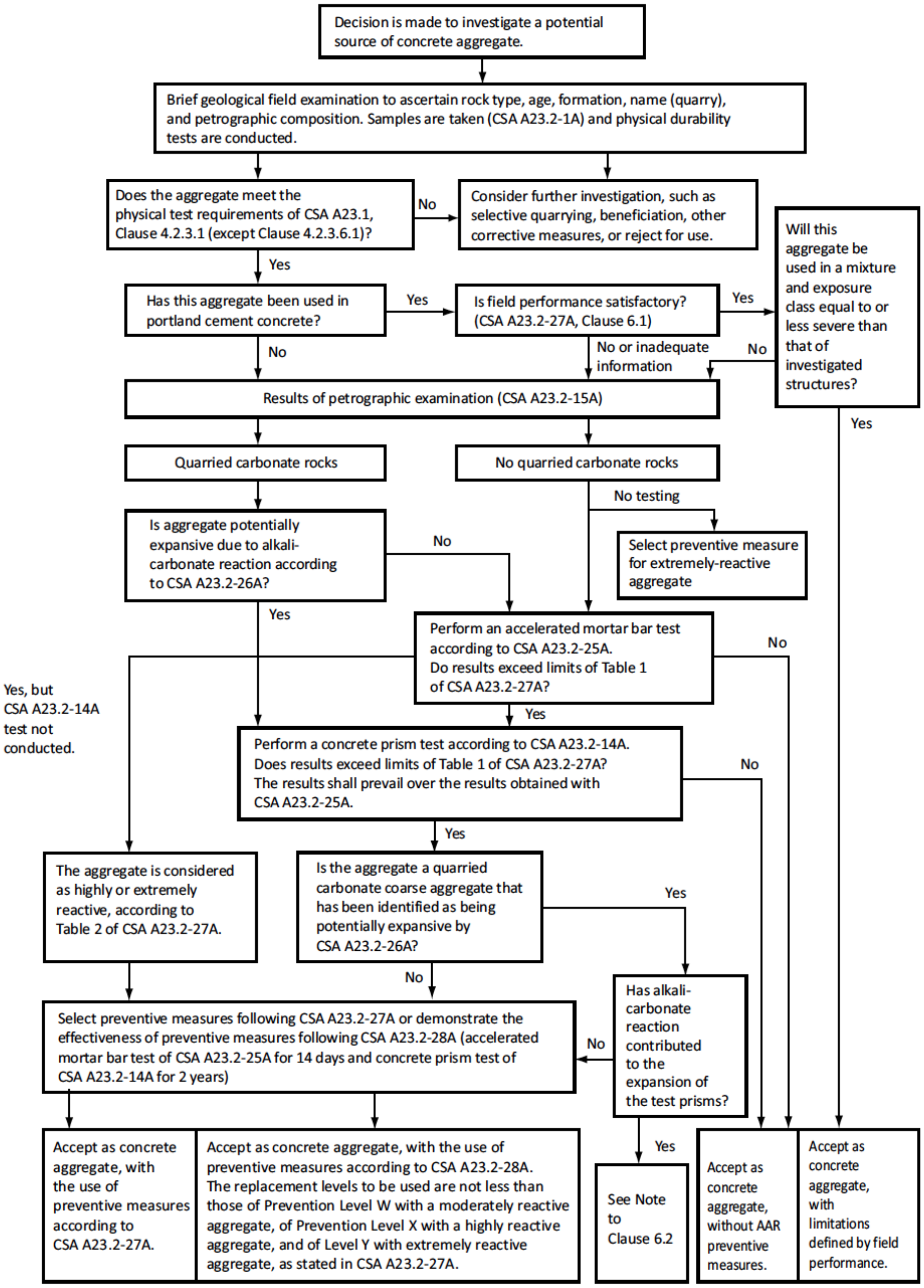


Figure 39. Flow chart from CSA A23.2-27-19 outlining the steps for determining aggregate reactivity and selecting appropriate preventive measures.

2.4.1.5 ACI 201.2R-16

ACI 201.2R-16 is a guide that provides information to the user within Chapter 5 as to how alkali-aggregate reactivity occurs and provides general commentary on the appropriate test methods to use and which to avoid. The document provides more of literature review-type background on the mechanisms and preventive measures for both alkali-silica and alkali-carbonate reaction. It then outlines many test methods (at the time of printing in 2016) and highlights advantages and disadvantages of those methods. It does not provide extensive detailed information on the RILEM test methods. Further, it does not cover some of the more recently developed methods that are outlined in this literature review. However, a Task Group is working on updating the AAR chapter of this document. One take away is that the generally recommended test methods include: ASTM C856, 1260, 1567 and C1293. They recommend that the user avoid these methods: ASTM C227, 289 and RILEM AAR-4 the accelerated concrete prism tests that runs at 60C. At the end of the chapter an approach to preventing alkali-silica reaction that references the approach in CSA A23.2-27A and ASTM C1778.

2.4.1.6 State Highway Agency Practice

Although it is expected that more state highway agencies will eventually follow the guidance in ASTM C1778 and AASHTO R80, there are currently a wide variety of approaches taken by the various agencies. To highlight these variations, the approaches taken by selected states (California, Texas, and Colorado) are briefly described next. Additional information will be collected during Phase II of this project, and a more comprehensive and up-to-date summary will be provided in the final project report.

California

The approach from the California DOT is remarkably similar to the prescriptive approach currently in ASTM C1778 and AASHTO R80. In this specification aggregate suppliers and concrete ready-mix producers are not asked to provide aggregate reactivity. They are simply instructed to use the following prescriptive approach if an aggregate is potentially alkali-silica reactive.

1. According to section 90-1.02B(3) of CalTrans Specifications 2018, Caltrans specifications for minimum SCM level for reactive aggregates:

Any combination of portland cement and at least 1 SCM, satisfying equations 1 and 2:

Equation 1: $[(25 \times UF) + (12 \times FA) + (10 \times FB) + (6 \times SL)]/MC \geq X$

where:

UF = silica fume, metakaolin, or Ultra-Fine Fly Ash (UFFA), including the quantity in blended cement, lb/cu yd

FA = natural pozzolan or fly ash complying with AASHTO M 295, Class F or N, with a CaO content of up to 10 percent, including the quantity in blended cement, lb/cu yd

FB = natural pozzolan or fly ash complying with AASHTO M 295, Class F or N, with a CaO content of greater than 10 percent and up to 15 percent, including the quantity in blended cement, lb/cu yd

SL = GGBFS, including the quantity in blended cement, lb/cu yd

MC = minimum quantity of cementitious material specified, lb/cu yd

X = 1.8 for innocuous aggregate, 3.0 for all other aggregate

Equation 2: $MC - MSCM - PC \geq 0$

where:
MC = minimum quantity of cementitious material specified, lb/cu yd
MSCM = minimum sum of SCMs that satisfies equation 1, lb/cu yd
PC = quantity of portland cement, including the quantity in blended cement, lb/cu yd

2. 15 percent Class F fly ash with at least 48 oz of $LiNO_3$ solution added per 100 lb of portland cement. The CaO content of the fly ash must not exceed 15 percent.

Texas

The Texas Transportation Department requires that one of the following eight options be followed when using reactive aggregates in transportation structures (TxDOT, 2014):

Option 1. Replace 20% to 35% of the cement with Class F fly ash.

Option 2. Replace 35% to 50% of the cement with slag cement or Modified Class F Fly Ash (MFFA).

Option 3. Replace 35% to 50% of the cement with a combination of Class F fly ash, slag cement, MFFA, UFFA, metakaolin, or silica fume; however, no more than 35% may be fly ash, and no more than 10% may be silica fume.

Option 4. Use Type IP, Type IS, or Type IT cement as allowed in Table 5 for each class of concrete. Up to 10% of a Type IP, Type IS, or Type IT cement may be replaced with Class F fly ash, slag cement, or silica fume. Use no more than 10% silica fume in the final cementitious material mixture if the Type IT cement contains silica fume, and silica fume is used to replace the cement.

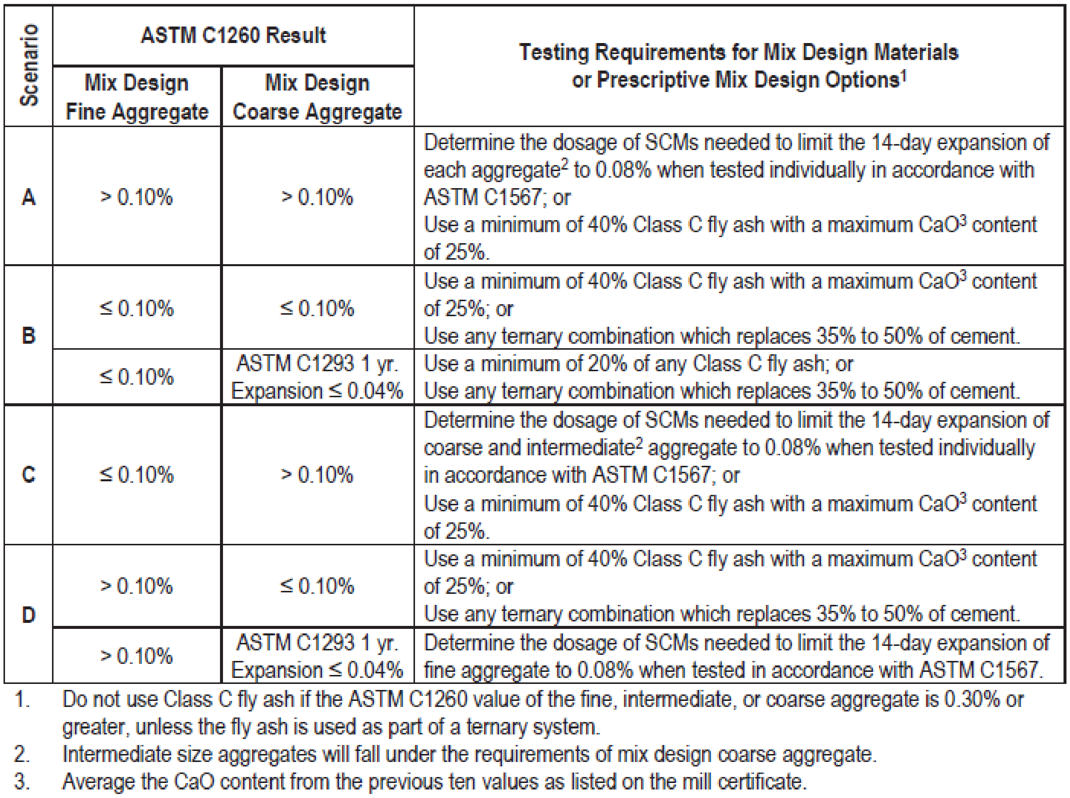
Option 5. Replace 35% to 50% of the cement with a combination of Class C fly ash and at least 6% of silica fume, UFFA, or metakaolin. However, no more than 35% may be Class C fly ash, and no more than 10% may be silica fume.

Option 6. Use a lithium nitrate admixture at a minimum dosage determined by testing conducted in accordance with Tex-471-A, "Lithium Dosage Determination Using Accelerated Mortar Bar Testing." Before use of the mix, provide an annual certified test report signed and sealed by a licensed professional engineer, from a laboratory on the Department's MPL, certified by the Construction Division as being capable of testing according to Tex-471-A, "Lithium Dosage Determination Using Accelerated Mortar Bar Testing."

Option 7. Ensure the total alkali contribution from the cement in the concrete does not exceed 3.5 lb. per cubic yard of concrete when using hydraulic cement not containing SCMs.

Option 8. Perform annual testing as required for any deviations from Options 1–5 or use mix design options listed in Table 10. Laboratories performing ASTM C1260, ASTM C1567, and ASTM C1293 testing must be listed on the Department's MPL. Before use of the mix, provide a certified test report signed and sealed by a licensed professional engineer demonstrating the proposed mixture conforms to the requirements shown in Table 14.

Table 14. TxDOT Option 8 testing and mix design requirements (TxDOT, 2014)



Scenario	ASTM C1260 Result		Testing Requirements for Mix Design Materials or Prescriptive Mix Design Options[1]
	Mix Design Fine Aggregate	Mix Design Coarse Aggregate	
A	> 0.10%	> 0.10%	Determine the dosage of SCMs needed to limit the 14-day expansion of each aggregate[2] to 0.08% when tested individually in accordance with ASTM C1567; or Use a minimum of 40% Class C fly ash with a maximum CaO[3] content of 25%.
B	≤ 0.10%	≤ 0.10%	Use a minimum of 40% Class C fly ash with a maximum CaO[3] content of 25%; or Use any ternary combination which replaces 35% to 50% of cement.
	≤ 0.10%	ASTM C1293 1 yr. Expansion ≤ 0.04%	Use a minimum of 20% of any Class C fly ash; or Use any ternary combination which replaces 35% to 50% of cement.
C	≤ 0.10%	> 0.10%	Determine the dosage of SCMs needed to limit the 14-day expansion of coarse and intermediate[2] aggregate to 0.08% when tested individually in accordance with ASTM C1567; or Use a minimum of 40% Class C fly ash with a maximum CaO[3] content of 25%.
D	> 0.10%	≤ 0.10%	Use a minimum of 40% Class C fly ash with a maximum CaO[3] content of 25%; or Use any ternary combination which replaces 35% to 50% of cement.
	> 0.10%	ASTM C1293 1 yr. Expansion ≤ 0.04%	Determine the dosage of SCMs needed to limit the 14-day expansion of fine aggregate to 0.08% when tested in accordance with ASTM C1567.

1. Do not use Class C fly ash if the ASTM C1260 value of the fine, intermediate, or coarse aggregate is 0.30% or greater, unless the fly ash is used as part of a ternary system.
2. Intermediate size aggregates will fall under the requirements of mix design coarse aggregate.
3. Average the CaO content from the previous ten values as listed on the mill certificate.

Colorado

The Colorado Highway Department specifies the use of ASTM C 1260 (AMBT) to determine aggregate reactivity. When an aggregate source is known to be reactive, ASTM C1567 results may be submitted in lieu of ASTM C1260 results. Any aggregate tested by ASTM C1260 with an expansion of 0.10 percent or more, or that is known to be reactive, shall not be used unless mitigative measures are included in the mix design. Test results from ASTM C1293 (CPT) may be substituted for ASTM C1260 test results. The ASTM C1293 test shall be run on an individual source of aggregate. The ASTM C1293 test shall not use pozzolan as part of the cementitious material content. Any aggregate source tested by ASTM C1293 with an expansion greater than or equal to 0.04 percent at one year shall not be used unless mitigative measures are included in the mix design.

Mitigative measures shall be tested using ASTM C1567 and exhibit an expansion less than 0.10 percent by one of the following methods:

(1) Combined Aggregates. The mix design sources of aggregates, cement and mitigative measures shall be tested. The proportions of aggregates, cement and mitigative measures shall be those used in the mix design.

(2) Individual Aggregates. Each source and size of individual aggregates shall be tested. The source of cement and mitigative measures shall be those used in the mix design. The highest level of mitigative measures for any individual aggregate shall be the minimum used in the mix design.

For all concrete mix designs with ASTM C150 cements, up to a maximum of 20 percent Class C fly ash, 30 percent Class F fly ash, or 30 percent high-reactivity pozzolan by weight of total cementitious material may be substituted for cement. Up to a maximum of 50 percent slag cement by weight of total cementitious material may be substituted for cement. When slag cement and pozzolans are substituted for cement, the total substitution of cement shall not exceed 50 percent by weight of total cementitious material.

3.0 References:

AFNOR NF P 18-454. 2004a. Reactivity of a concrete formula with regard to the alkali-aggregate reaction, Association Française de Normalisation, Paris, France, December 2004.

AFNOR NF P 18-456, 2004b. Reactivity of a concrete formula with regard to the alkali-aggregate reaction - Criteria for interpretation of the performance test results, Association Française de Normalisation, Paris, France November 2004.

AASHTO Designation T 380-19. 2019. Potential Alkali Reactivity of Aggregates and Effectiveness of ASR Mitigation Measures (Miniature Concrete Prism Test, MCPT), American Association of State Highway and Transportation Officials (AASHTO), Washington, DC (USA), 10 p.

AASHTO Designation T 364-17. 2017. Determination of Composite Activation Energy of Aggregates due to Alkali–Silica Reaction (Chemical Method), American Association of State Highway and Transportation Officials (AASHTO), Washington, DC (USA), 15 p.

AASHTO Designation T 379-18. 2018. Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) for Concrete Specimens with Damage from the Alkali–Silica Reaction (ASR), Washington, DC (USA), 7 p.

ASTM C 1778-19. 2019. Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate reaction in Concrete. ASTM - Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

AASHTO Designation R 80-17. 2017. Standard practice for determining the reactivity of concrete aggregates and selecting appropriate measures for preventing deleterious expansion in new concrete construction, American Association of State Highway and Transportation Officials (AASHTO), Washington, DC (USA), 25p.

ASTM C295-12. 2014. Standard guide for petrographic examination of aggregates for concrete. ASTM - Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

ASTM C1260-14. 2014. Standard Test Method for Potential Alkali Reactivity of Aggregates (mortar bar method). ASTM - Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

ASTM C1293-08b. 2014. Standard method for determination of length change of concrete due to alkali silica ASTM - Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

ASTM C 1778-14. 2014. Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate reaction in Concrete. ASTM - Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

ASTM C 1778-19a. 2019. Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate reaction in Concrete. ASTM - Annual Book of ASTM Standards 04.02, ASTM International, West Conshohocken (USA).

Berube, M.A. and Frenette, J. 1994. "Testing Concrete for AAR in NaOH and NaCl Solutions at 38°C and 80°C." *Cement and Concrete Composites*, Vol. 16, No.3, pp. 189-198.

Bhatty, M.S.Y. and Greening, N.R. 1978. "Interaction of alkalis with hydrating and hydrated calcium silicates." *Proceedings of the Fourth International Conference on the Effects of Alkalis in Cement and Concrete,* Purdue, 87-112.

Bleszynski, R.F. 2002. "The performance and durability of concrete with ternary blends of silica fume and blast-furnace slag." PhD Thesis, University of Toronto.

BS 812-104: 1994 Testing aggregates. Method for qualitative and quantitative examination of aggregates. BSI Global, London.

Chappex, T. and Scrivener,K., "Alkali Fixation of C-S-H in Blended Cement Pastes and Its Relation to Alkali Silica Reaction," *Cement and Concrete Research*, Vol. 42, No. 8, 2012, pp. 1049-1054. http://dx.doi.org/10.1016/j.cemconres.2012.03.010

Chatterji, S., Thaulow, N., and Jensen A.D. 1987. "Studies of ASR: Part 4." *Cement and Concrete Research,* Vol. 17, pp. 777-783.

Chopperla, K.S.T., Drimalas, T., Tanesi, J., Ardani, A., Laskey, M., Thomas, M., Folliard, K., and Ideker J., "Bench-marking the Miniature Concrete Prism Test and the Concrete Cylinder Tests to Field Exposure Blocks for Mitigation of Alkali-silica Reaction," *in Proceedings of the 15th International Congress on the Chemistry of Cement, Research Institute of Binding Materials Prague*, Prague, Czech Republic, September 2019, 10 pp.

CSA A23.2-25A. 2014. Test method for detection of alkali-silica reactive aggregate by accelerated expansion of mortar bars. CSA A23.1 (Concrete materials and methods of concrete construction) & A23.2 (Test methods and standard practices for concrete), Canadian Standards Association, Mississauga, Ontario, Canada, 425-433.

CSA A23.2-14A. 2014. Potential Expansivity of Aggregates (Procedure for length change due to Alkali-Aggregate Reactions in Concrete Prisms at 38°C). CSA A23.1 (Concrete materials and methods of concrete construction) & A23.2 (Test methods and standard practices for concrete), Canadian Standards Association, Mississauga, Ontario, Canada, 350-362.

CSA A23.2-27A. 2014. Standard practice to identify degree of alkali-reactivity of aggregates and to identify measures to avoid deleterious expansion in concrete. CSA A23.1 (Concrete materials and methods of concrete construction) & A23.2 (Test methods and standard practices for concrete), Canadian Standards Association, Mississauga, Ontario, Canada, 439-451.

CSA A23.2-28A. 2014. Standard Practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete. CSA A23.1 (Concrete materials and methods of concrete construction) & A23.2 (Test methods and standard practices for concrete), Canadian Standards Association, Mississauga, Ontario, Canada, 452-457.

Dent Glasser, L.S. and Kataoka, N. 1981a. "The chemistry of alkali-aggregate reactions", *Proceedings of the 5th International Conference on Alkali-Aggregate Reaction*, Cape Town, S252/23.

Dent Glasser, L.S. and Kataoka, N. 1981b. "The chemistry of alkali-aggregate reactions", *Cement and Concrete Research,* Vol. 11, pp. 1-9.

Duchesne, J., and Berube, M.A. 1996. "Effect of Deicing Salt and Sea Water on ASR: New Considerations Based on Experimental Data." *Proceedings of 10th International Conference on Alkali-Aggregate Reactions*, Melbourne, Australia, pp. 19-23.

Feng, X., Thomas, M.D.A., Bremner, T.W., Balcom, B.J. and Folliard, K.J. 2005. "Studies on lithium salts to mitigate ASR-induced expansion in new concrete: a critical review." *Cement and Concrete Research,* 35: 1789-1796.

Fernandes, I., Ribeiro, A.Md., Broekmans, M.A.T.M., Sims, I. 2016a. Petrographic atlas: characterisation of aggregates regarding potential reactivity to alkalis. RILEM TC 219-ACS Recommended Guidance AAR-1.2, for use with the RILEM AAR-1.1 Petrographic Examination Method, Springer, Dordrecht, RILEM, Paris, 204 pp.

FGSV. 2018. Forschungsgesellschaft für Straßen- und Verkehrswesen (Ed.): TP B-StB - Technische Prüfvorschriften für Verkehrsflächenbefestigungen - Betonbauweisen: Teil 1.1.09 AKR-Potenzial und Dauerhaftigkeit von Beton (60 °C-Betonversuch mit Alkalizufuhr). Köln: FGSV-Verl., 2018

Folliard, K.J., Barborak, R., Drimalas, T., Du, L., Garber, S., Ideker, J., Ley, T., Williams, S., Juenger, M., Thomas, M.D.A., and Fournier, B., "Preventing ASR/DEF in New Concrete: Final Report," The University of Texas at Austin, Center for Transportation Research (CTR), CTR 4085-5, 2006.

Folliard, K.J., Thomas, M.D.A., Fournier, B. 2008. "The effects of potassium acetate de-icing chemicals on the performance of concrete containing fly ash: a literature review", EPRI Report 1018167, Electrical Power Research Institute, Palo Alto, CA.

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

Fournier, B., Nkinamubanzi, P.-C. & Chevrier, R. (2004) Comparative field and laboratory investigations on the use of supplementary cementing materials to control Alkali-Silica reaction in concrete. In: Mingshu, T. and Min, D. (eds.) *Proceedings of the 12th International Conference Alkali-Aggregate Reaction in Concrete*, Vol. 1, International Academic Publishers/World Publishing Corporation, Beijing, China, pp. 528–537.

Giannini, E.R., Folliard, K.J., A Rapid Test to Determine Alkali-Silica Reactivity of Aggregates Using Autoclaved Concrete Prisms, Portland Cement Association, SN3235, 2013.

Glasser, F.P. 1992. "Chemistry of the alkali-aggregate reaction." The Alkali-Silica Reaction in Concrete (Ed. R.N. Swamy), Blackie, London, 96-121.

Glasser, F.P. and Marr, J. 1985. “The alkali binding potential of OPC and blended cements.” Il Cemento, 82: 85-94.

Grattan-Bellew, P.E., Cybanski, G., Fournier, B., Mitchell, L. 2003. Proposed universal accelerated test for alkali-aggregate reaction the concrete microbar test. *Cement, Concrete Aggregates*, 25(2): 29–34.

Grattan-Bellew, P.E. 1989. Mechanism of alkali-aggregate reactions. Proceedings of the 20th Acres Geotechnical seminar on AAR in hydraulic structures. Acres International Ltd. 20p.

Hong, S-Y and Glasser, F.P. 1999. “Alkali binding in cement pastes Part I. The C-S-H phase.” *Cement and Concrete Research*, 29: 1893-1903.

Hong, S-Y and Glasser, F.P. 2002. “Alkali sorption by C-S-H and C-A-S-H gels Part II. Role of alumina.” *Cement and Concrete Research*, 32: 1101-1111.

Hayman, S., Thomas, M.D.A., Beaman, N. and Gilks, P. 2010. “Selection of an effective ASR-prevention strategy for use with a highly reactive aggregate for the reconstruction of concrete structures at Mactaquac generating station.” *Cement and Concrete Research*, Vol. 40, pp. 605-610.

Hayman, S., Drimalas, T., Thomas, M.D.A. and Folliard, K. 2012. “Potassium acetate and ASR.” *Proceedings 14th International Conference on Alkali-Aggregate Reactions,* Austin, TX, May 2012.

Helmuth, R., Stark, D., Diamond, S., Moranville-Regourd, M., “Alkali-Silica Reactivity: An Overview of Research.” Strategic Highway Research Program. SHRP-C-342. 1993.

Hooton, R.D., Rogers, C.A., MacDonald, C.A., and Ramlochan, T. 2013. “20-year field evaluation of alkali-silica reaction mitigation. *ACI Mater J.*, 110 (5), 539–548.

Ideker, J. H., T. Drimalas, A. F. Bentivegna, K. J. Folliard, B. Fournier, M. D. A. Thomas, R. D. Hooton and C. A. Rogers, “The Importance of Outdoor Exposure Site Testing, in *Proceedings 14th International Conference on Alkali-Aggregate Reaction*,” Drimalas, T., Ideker, J.H., and Fournier, B. eds. Austin, TX, 2012, 10 pp.

Japan Concrete Institute: Committee report of JCI-TC-152A. 2017. Technical Committee on Performance Based Design and Maintenance Scenario with Controlling ASR Deterioration (in Japanese).

Kawamura, M. and Ichise, M. 1990. "Characteristics of ASR in Presence of Sodium and Calcium Chloride." *Cement and Concrete Research*, Vol. 20, No.5, pp. 757-766.

Kawamura, M., Takeuchi, K., and Sugiyama, A. 1994. "Mechanisms of expansion of mortars containing reactive aggregates in NaCl solution." *Cement and Concrete Research*, Vol. 24, pp. 621-632.

Latifee, E.R. and Rangaraju, P.R. “Miniature Concrete Prism Test – Rapid Test Method for Evaluating Alkali Silica Reactivity of Aggregates” *ASCE Journal of Materials in Civil Engineering*, 2014.

Lindgård, J., Nixon P.J., Borchers, I., Schouenborg, B., Wigum B.J., Haugen M., Akesson, U. 2010. The EU “PARTNER” Project-European standard tests to prevent alkali reactions in aggregates: Final Results and Recommendations, *Cement and Concrete Research*, 40 (4): 611-635.

MacDonald, C.A., Rogers, C. and Hooton, R.D., 2012. The relationship between laboratory and field expansion–observations at the Kingston outdoor exposure site for ASR after twenty years. In *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction in Concrete*, Austin, TX, USA, May.

McCoy, W.J. and Caldwell, A.G. 1951. “New approach to inhibiting alkali-aggregate expansion.” *Journal of the American Concrete Institute*, 22(9): 693-706.

Nishibayashi, S., Yamura, K., Matsushita, H., A Rapid Method of Determining the Alkali-Aggregate Reaction in Concrete by Autoclave, *7th International Conference on Alkali-Aggregate Reaction in Concrete*, Ottawa, ON, Canada, 1987.

Nishibayashi, S., Kuroda, T., Inoue, S., Okawa, Y., Expansion Characteristics of AAR in Concrete by Autoclave Method, *Proceedings of the 10th International Conference on Alkali-Aggregate Reaction*, Australia, 1996, 370-376.

Nixon, P.J., Page, C.L., Canham, I., and Bollinghaus, R. 1988. "Influence of sodium chloride on the ASR." *Advances in Cement Research*, Vol. 1, pp. 99-105.

Nixon. P., Fournier, B. 2017. Assessment, testing and Specification. Chapter 2 in Alkali-Aggregate Reaction – a World Review. Sims, I. and Poole, A. (Editors), CRC Press (Taylor & Francis Group), 768p.

Oberholster, R.E. and Davies, G., "An Accelerated Method for Testing the Potential Alkali Reactivity of Siliceous Aggregates," *Cement and Concrete Research*, 1986, V 16 [2], pp. 181-189.

Pedneault, A. 1996. "Development of testing and analytical procedures for the evaluation of the residual potential of reaction, expansion, and deterioration of concrete affected by ASR." M.Sc. Memoir, Laval University, Québec City, Canada, 133 p.

Plusquellec, G., & De Weerdt, K. (2017). Cold water extraction (CWE). Procedure for the determination of the alkali content and pore solution composition.

Ramlochan, T., Thomas, M.D.A. and Gruber, K.A. 2000. "The effect of metakaolin on alkali-silica reaction in concrete." *Cement and Concrete Research*, 30(3): 339-344.

Rangaraju, P.R. and Olek, J. 2007. "Potential for acceleration of ASR in the presence of pavement deicing chemicals." Report IPRF-01-G-002-03-9, Innovative Pavement Research Foundation, Skokie, IL.

Rangaraju, P.R., Sompura, K.R. and Olek, J. 2007. "Modified ASTM C 1293 test method to investigate potential of potassium acetate deicer solution to cause alkali-silica reaction." Transportation Research Record: *Journal of the Transportation Research Board*, No. 2020, pp. 50-60.

Rangaraju, P., Afshinnia, K., Enugula, S., and Latifee, E., (2016). Evaluation of alkali-silica reaction potential of marginal aggregates using Miniature Concrete Prism Test (MCPT).

Rayment, P.L. 1982. "The effect of pulverized-fuel ash on the C/S molar ratio and alkali content of calcium silicate hydrates in cement." *Cement and Concrete Research*, 12(2): 133-140.

RILEM. 2000. Recommended test method TC 106-03, Detection of potentially alkali-reactivity of aggregates: A. The Ultra-accelerated mortar-bar test; B: Method for aggregate combinations using concrete prisms, *Materials and Structures*, 33: 283–293.

RILEM. 2016. RILEM recommendations for the prevention of damage by alkali-aggregate reactions in new concrete structures. *RILEM State-of-the-Art Reports*, Volume 17, Springer, Dordrecht, Nixon, P.J., Sims, I., 168pp.

RILEM. 2003a. RILEM Recommended Test Method AAR-0: Detection of Alkali-Reactivity Potential in Concrete—Outline guide to the use of RILEM methods in assessments of aggregates for potential alkali-reactivity. *Materials and Structures*, 36 (7): 472–479

RILEM. 2003b. RILEM Recommended Test Method AAR-1: Detection of potential alkali-reactivity of aggregates—petrographic method. *Materials and Structures*, 36 (7): 480–496.

RILEM 2018a. Method AAR-8: Determination of Alkalis Releasable by Aggregates in Concrete, Draft procedure prepared by Esperanza Menéndez, António Santos Silva, Josée Duchesne. RILEM TC-258-AAA, Work Package 3 material.

RILEM 2018b. Draft RILEM Recommended Test Method: AAR-10. Determination of binder combinations for non-reactive mix design using concrete prisms – 38°C test method. Draft procedure prepared by T.F. Rønning and members of Work Package 1 of RILEM TC-258-AAA. Work Package 1 material.

RILEM 2018c. Draft RILEM Recommended Test Method: AAR-11. Determination of binder combinations for non-reactive mix design or the resistance to alkali-silica reaction of concrete mixes using concrete prisms – 60°C test method. Draft procedure prepared by I. Borchers and members of Work Package 1 of RILEM TC-258-AAA. Work Package 1 material.

RILEM 2018d. Draft RILEM Recommended Test Method: AAR-12. Determination of Binder Combinations for Non-reactive Mix Design or the resistance to ASR of Concrete Mixes Using Concrete Prisms – 60°C Test Method with alkali supply. Draft procedure prepared by I. Borchers and members of Work Package 1 of RILEM TC-258-AAA. Work Package 1 material.

RILEM 2018e. Draft RILEM Recommended Test Method: AAR-13. Application of Alkali-wrapping for Concrete Prism Testing Assessing the Expansion Potential by Alkali-Silica Reaction. Draft procedure prepared by K. Yamada and members of Work Package 1 of RILEM TC-258-AAA. Work Package 1 material.

SA HB 79:2015. Handbook – Alkali aggregate reaction – Guidelines on minimizing the risk of damage to concrete structures in Australia. SAI Global Limited, Sydney, Australia, 78p

Shehata, M., Thomas, M.D.A. and Bleszynski, R.F. 1999. “The effect of fly composition on the chemistry of pore solution.” *Cement and Concrete Research,* 29(12): 1915-1920.

Shehata, M.H. and Thomas, M.D.A. 2000. “The effect of fly ash composition on the expansion of concrete due to alkali-silica reaction.” *Cement and Concrete Research,* 30: 1063-1072.

Shehata, M.H. and Thomas, M.D.A. 2002. “Use of ternary blends containing silica fume and fly ash to suppress expansion due to alkali-silica reaction in concrete*.” Cement and Concrete Research*, 32(3): 341-349.

Shehata, M. H. and M. D. A. Thomas (2006). "Alkali release characteristics of blended cements." Cement and Concrete Research **36**(6): 1166-1175.

Sibbick, R.G. and Page C.L. 1996. "Effects of Sodium Chloride in Alkali Silica Reactions in Hardened Concretes." *Proceedings of 10th International Conference on Alkali Aggregate Reactions,* Melbourne, Australia, pp. 822-829.

Stacey, S., Folliard, K.J., Drimalas, T., and Thomas, M.D.A., “An Accelerated and More Accurate Test Method to ASTM C 1293: The Concrete Cylinder Test,” *Proceedings of the 15th International Conference on Alkali-Aggregate Reactivity (ICAAR)*, Sao Paolo, Brazil, ISSN 2525-3247, 15ICAAR2016_130, July 2016.

Stanton, T.E. 1940. “Expansion of concrete through reaction between cement and aggregate”, Proceedings of the American Society of Civil Engineers, 66(10), 1781-1811.

Stanton, T.E. 1950. "Studies of use of pozzolans for counteracting excessive concrete expansion resulting from reaction between aggregates and the alkalies in cement." *Pozzolanic Materials in Mortars and Concretes*, ASTM STP 99, American Society for Testing and Materials, Philadelphia, 178-203.

Swenson, E.G. 1957. “A reactive aggregate undetected by ASTM tests”, *Proceedings of American Society for Testing and Materials*, 57, 48-51.

Tamura, H., A test method on rapid identification of alkali reactivity of aggregates (GBRC rapid method), *7th International Conference on Alkali-Aggregate Reaction in Concrete*, Ottawa, ON, Canada, 1987, 304-308.

Tang, M., Han, S., Zhen, S., A Rapid Method for Identification of Alkali Reactivity of Aggregate, *Cement and Concrete Research*, 13, 1983, 417-422.

Texas Department of Transportation (TxDOT), Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges, 2014.

Thomas, M.D.A. 2011. “The effect of supplementary cementing materials on alkali-silica reaction: A review.” *Cement and Concrete Research*, Vol. 41, pp. 1224-1231.

Thomas, M.D.A. and Hayman, S., 2011. Deterioration of cement paste exposed to potassium acetate solution. XIII ICCC. In International Congress on the Chemistry of Cement, Spain, Madrid.

Thomas, M.D.A., Fournier, B., Folliard, K.J. 2013. “Alkali-Aggregate Reactivity (AAR) Facts Book.” Federal Highways Administration Report FHWA-HIF-13-019, U.S. Department of Transportation, Washington, D.C.

Thomas, M.D.A., Hooton, R.D., and Folliard, K.J. 2017a. “Prevention of alkali-silica reaction.” In Alkali-Aggregate Reaction in Concrete – A World Review, Ed. I. Sims and A. Poole, CRC Press, pp. 89-118.

Thomas, M.D.A., Folliard, K.J. and Ideker, J.H. 2017b. “North America (USA and Canada.” In Alkali-Aggregate Reaction in Concrete – A World Review, Ed. I. Sims and A. Poole, CRC Press, pp. 467-491.

Thomas MDA, "Delayed Ettringite Formation: Recent Developments and Future Directions." *Materials Science of Concrete* VI, (Ed. S. Mindess and J. Skalny), American Ceramics Society, Westerville, OH, 2001, pp. 435-482.

Thomas, M.D.A., Folliard, K., Drimalas, T. and Ramlochan, T. 2008. “Diagnosing delayed ettringite formation in concrete structures.” *Cement and Concrete Research*, Vol. 38, pp. 841-847.

Thomas, M.D.A. and Folliard, K.J. 2007. “Concrete aggregates and the durability of concrete.” *Durability of concrete and cement composites*, (Ed. C.L. Page and M.M. Page), Woodhead, Cambridge, U.K. 247-281.

Thomas, M.D.A. and Innis, F.A. 1998. “Effect of slag on expansion due to alkali-aggregate reaction in concrete.” *ACI Materials Journal*, 95(6): 716-724.

Tremblay, C., Berube, M-A., Fournier, B., Thomas, M.D.A. and Folliard, K.F. 2007. “Effectiveness of lithium-based products in concrete made with Canadian reactive aggregates.” *ACI Materials Journal*, 104(2): 195-205.

Uchikawa, H., Uchida, S. and Hanehara, S. 1989. "Relationship between structure and penetrability of Na ion in hardened blended cement paste mortar and concrete." *Proceedings of the 8th International Conference on Alkali-Aggregate Reaction*, (Ed. K.Okada, S. Nishibayashi and M. Kawamura), Kyoto, 121-128.

Vivian, H.E., 1950, April. Some Australian Studies on Cement-Aggregate Reaction in Mortar. In Journal Proceedings (Vol. 46, No. 4, pp. 617-621).

Wood, S.G. “Investigation of Autoclave Methods for Determining Alkali-Silica Reactivity of Concrete Aggregates”, PhD Dissertation, The University of Alabama, Tuscaloosa, Alabama, USA, 2017.

Wood, S.G.; Giannini, E.R.; Ramsey, M.A.; Moser, R.D. Autoclave Test Parameters for Determining Alkali-Silica Reactivity of Concrete Aggregates. *Construction and Building Materials*, 168, 2018, 683-691.

Wood, S.G.; Giannini, E.R.; Bentivegna, A.F.; Rashidian-Dezfouli, H.; Rangaraju, P.R.; Drimalas, T.; Ramsey, M.A.; Johnson, T.R.; Moser, R.D. Five-hour autoclave test for determining potential alkali-silica reactivity of concrete aggregates: a multi-laboratory study. *Advances in Civil Engineering Materials*, 6(1) 2017, 550-563.