Report on Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction

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16. Abstract

Alkali-aggregate reactions (AAR) occur between the alkali hydroxides in the pore solution of concrete and certain minerals found in some aggregates. Two types of AAR reaction are currently recognized depending on the nature of the reactive mineral; alkali-silica reaction (ASR) involves various types of reactive silica (SiO_2) minerals and alkali-carbonate reaction (ACR) involves certain types of dolomitic rocks ($CaMg(CO_3)_2$). Both types of reaction can result in expansion and cracking of concrete elements, leading to a reduction in the service life of concrete structures.

This report describes approaches for identifying deleteriously reactive aggregates and selecting appropriate preventive measures to minimize the risk of expansion when such aggregates are used in concrete. Preventive measures include avoiding the reactive aggregate, limiting the alkali content of the concrete, using supplementary cementing materials, using lithium-based admixtures, or a combination of these strategies.

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Report A: Determining The Reactivity Of Concrete Aggregates And Selecting Appropriate Measures For Preventing Deleterious Expansion In New Concrete Construction

1.0 Introduction

Alkali-aggregate reactions (AAR) occur between the alkali hydroxides in the pore solution of concrete and certain minerals found in some aggregates. Two types of AAR reaction are currently recognized depending on the nature of the reactive mineral; alkali-silica reaction (ASR) involves various types of reactive silica (SiO_2) minerals and alkali-carbonate reaction (ACR) involves certain types of dolomitic rocks ($CaMg(CO3)_2$). Both types of reaction can result in expansion and cracking of concrete elements, leading to a reduction in the service life of concrete structures.

This report describes approaches for identifying deleteriously reactive aggregates[1] and selecting appropriate preventive measures to minimize the risk of expansion when such aggregates are used in concrete. Preventive measures include avoiding the reactive aggregate, limiting the alkali content of the concrete, using supplementary cementing materials, using lithium-based admixtures, or a combination of these strategies.

2.0 General Approach

The flow chart in Figure 1 shows the general sequence of testing and decisions that have to be made when evaluating a source of aggregate for potential AAR. Prior satisfactory field performance of the aggregate in concrete is considered in some cases to be sufficient for its acceptance in new concrete. However, the use of field performance in the absence of testing may not be sufficient to completely safeguard against damage due to AAR in new construction because of the difficulties in assuring that the materials used in existing structures built ten to twenty years ago (time frame needed to ensure that AAR has not occurred) are similar to those being proposed for use today. In most cases, it will be necessary to conduct laboratory tests to determine whether or not the aggregate is deleteriously reactive. There are many test methods available for evaluating aggregate reactivity, but only two ex pansion tests, together with petrographic examination are recommended in this report. If the aggregate is deemed to be non-deleteriously-reactive, it can be accepted for use in concrete with no further consideration of mitigation (assuming that the physical properties of the aggregate render it suitable for use). If the aggregate is found to be deleteriously reactive, it must then be determined whether the reaction is of the alkali-carbonate or alkali-silica type. There are no proven measures for effectively preventing damaging expansion with alkali-carbonate reactive rocks and such materials must be avoided by selective quarrying or beneficiation. If the aggregate is alkali-silica reactive, the aggregate may be either rejected for use or accepted with an appropriate preventive measure.

[1]The term deleteriously reactive is used to define aggregates that undergo chemical reactions in concrete which subsequently result in damage to the concrete. Some aggregates with minor amounts of reactive constituents may exhibit some small amount of reaction without producing any damage to the concrete; these are non-deleteriously reactive aggregates.

There are a number of options for minimizing the risk of expansion with alkali-silica reactive rocks. This report allows for preventive measures to be evaluated on the basis of performance testing or to be selected prescriptively from a list of options based on previous experience.

In the approach outlined by this report, the level of testing and the test limits vary depending on the level of risk that is acceptable to the owner. For example, in regions where occurrences of AAR are rare or where the aggregate sources in use have a long history of good field performance; it may be reasonable to continue to rely on the previous field history without subjecting the aggregates to laboratory tests. However, in regions where AAR problems are not infrequent and where the reactivity of aggregates are known to vary from source to source, it may be necessary to implement a rigorous testing regime to establish aggregate reactivity and evaluate preventive measures. In the report described here the level of prevention required is a function of the reactivity of the aggregate, the nature of the exposure conditions, and the availability of alkali in the system.

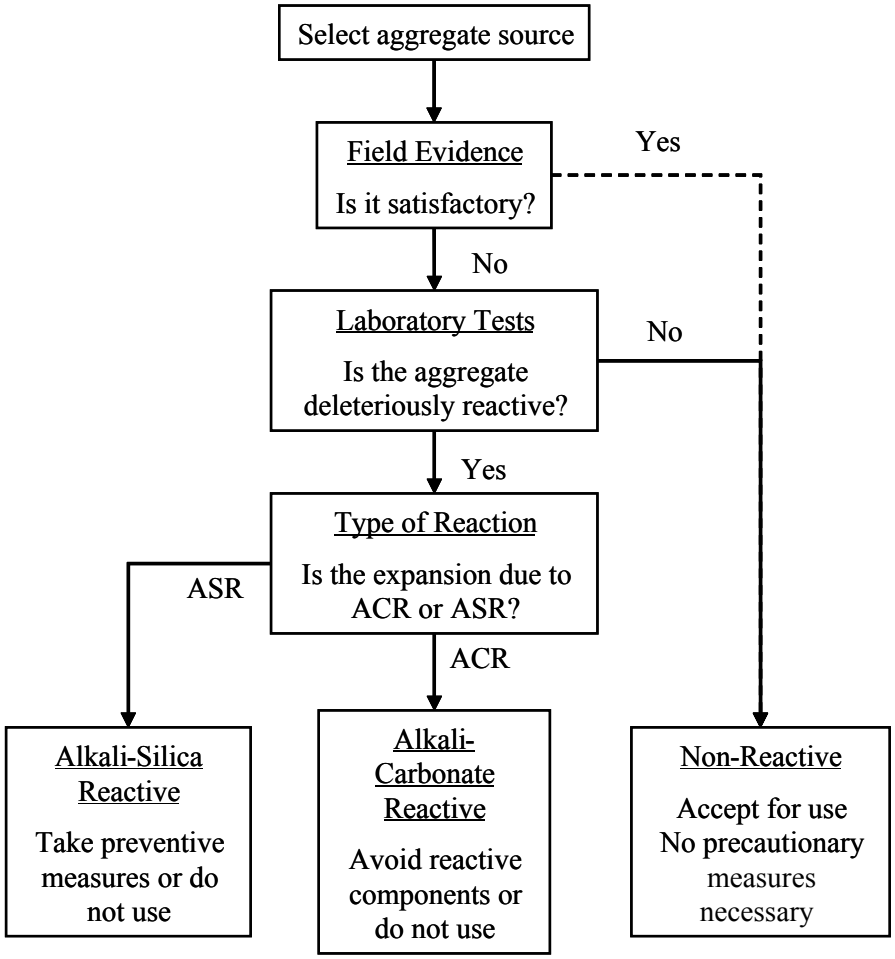

Figure 1. Summary of the Various Stages in the Process of Evaluation

3.0 Testing To Determine Aggregate Reactivity

Figure 2 shows a flow chart of the sequence of testing for this report when evaluating the reactivity of an aggregate source. Selecting an appropriate preventive measure will be dealt with in the next section. Interpreting the results from these aggregate tests is discussed at the end of this section (see Section 3.6 below).

3.1. Use of Field Performance History

The long-term field performance history of an aggregate can be established by conducting a survey of existing structures that were constructed using the same aggregate source. As many structures as practical should be included in the survey and these structures should, where possible, represent different types of construction (pavements, sidewalks, curb and gutter, elements of bridges, barrier walls and even non-transportation structures). The following information should be collected for each structure:

- Age – structures should be at least 10 years old and preferably more than 15 years old as dam age due to AAR can take more than ten years to develop.
- Cement content and alkali content of the cement used during construction.
- Use of pozzolans or slag during construction.
- Exposure condition – availability of moisture, use of deicing chemicals.
- Presence of symptoms of distress due to AAR or other causes.

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Cores should be taken from a representative number of these structures and a petrographic examination be conducted in accordance with ASTM C 856 to establish the following:

- The aggregate used in the structures surveyed is close in mineralogical composition to that of the aggregate currently being produced.
- There is no evidence of damage due to AAR.
- The presence and quantity of fly ash or slag.

If the results of the field survey indicate that the aggregate is non-deleteriously reactive, the aggregate may be used in new construction provided that the new concrete is not produced with a higher cement alkali loading, lower amount of pozzolan or slag, or more aggressive exposure condition than the structures included in the survey.

There is a certain level of risk associated with accepting aggregates solely on the basis of field performance due to difficulties in establishing unequivocally that the materials and proportions used more than 10 to 15 years ago are similar to those to be used in new construction.

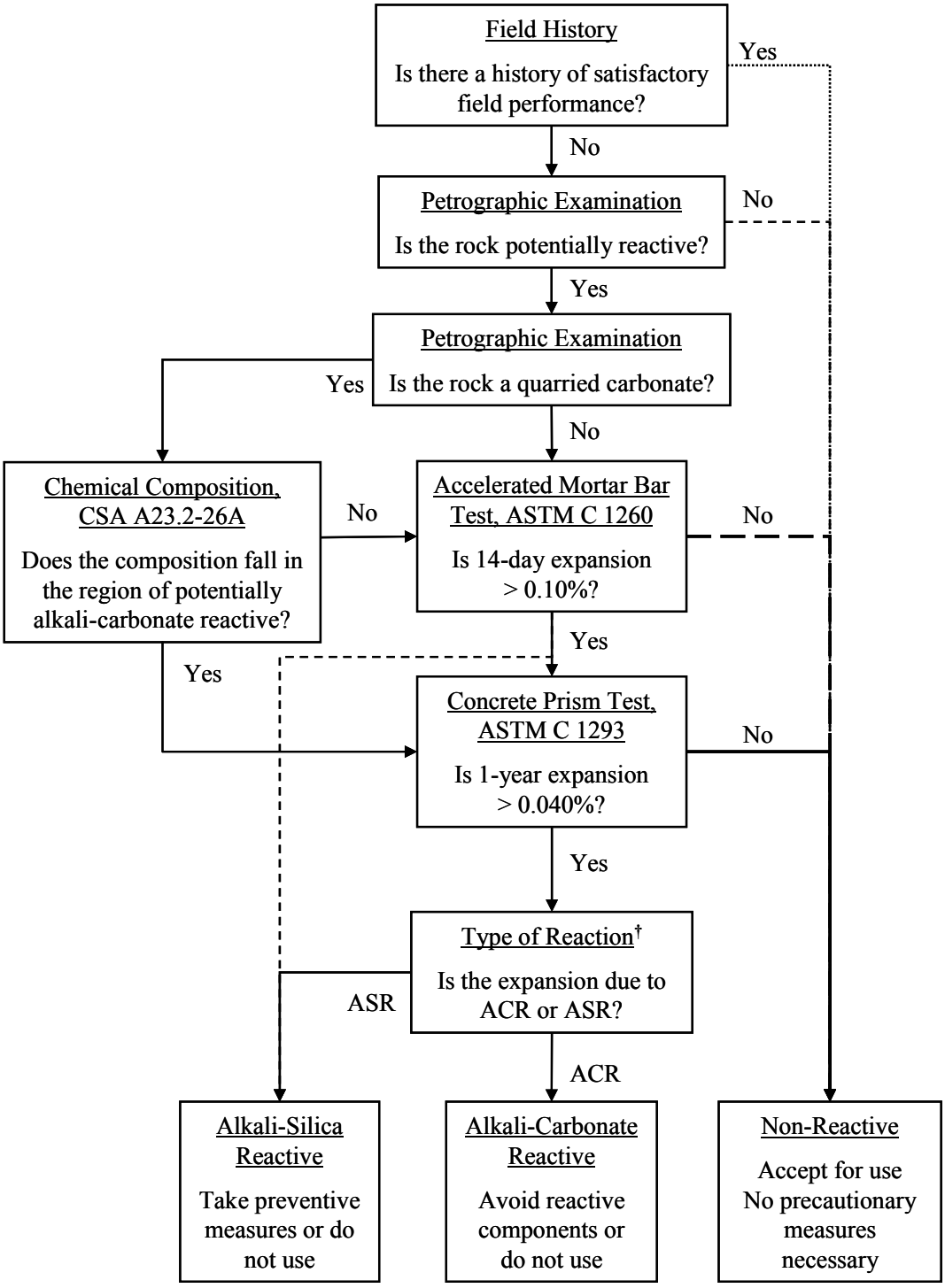

Figure 2. Sequence of Laboratory Tests for Evaluating Aggregate Reactivity

†The type of reaction only needs to be determined after the concrete prism test if the aggregate being tested is a quarried carbonate that has been identified as being potentially alkali-carbonate reactive by chemical composition in accordance with test method CSA A23.2-26A

†Note: The heavier dotted lines represent the preferred approach whereas the faint dotted lines represent a higher risk approach.

If field performance indicates that an aggregate source is deleteriously reactive, laboratory expansion testing is required to determine the level of aggregate reactivity and to evaluate prevention measures.

3.2. Petrographic Assessment

Petrographic examination of aggregates should be conducted in accordance with ASTM C 295. Petrography can reveal useful information about the composition of an aggregate, including the identification and approximate quantification of reactive minerals. Petrography may be used to classify an aggregate as potentially reactive, but expansion testing is required to determine the extent of the reactivity and appropriate levels of prevention. Aggregates may be accepted as non-reactive solely on the basis of petrography but there is certain level of risk associated with such a decision as some reactive phases may not be detected by optical microscopy (e.g. finely dispersed opaline silica found in some siliceous limestones). Where a trained petrographer is examining aggregates from well-known and tested sources, it is acceptable to use petrography to classify the aggregate reactivity on a routine basis. For example, in deposits where chert is known to be the only reactive component and where testing has shown that the chert content needs to exceed 5% to cause deleterious reaction, it may be justified to permit acceptance of an aggregate with less than say 3% chert on the basis of petrography.

In addition to looking for alkali-silica reactive minerals such as opal, chalcedony, cristobalite, tridymite, strained and micro-crystalline quartz, and volcanic glass, petrographers should also be vigilant as to the presence of mineralogical and textural features characteristic of alkali-carbonate rocks. Deleterious alkali-carbonate reactive rocks are often characterized by a microscopic texture consisting of dolomitic rhombs floating in a fine-grained matrix of calcite, quartz and clay. However, there have been reports of deleterious ACR with rocks that do not exhibit this "classic" texture (Ozol, 2006).

3.3. Determination of Potential Alkali-Carbonate Reactive Rocks by Chemical Composition, CSA A23.2-26A

If the aggregate being assessed is a quarried carbonate rock, the potential for alkali-carbonate reaction may be assessed on the basis of its chemical composition (Rogers, 1986). This is the basis for the test method CSA A23.2-26A .[2] This test involves the determination of the lime (CaO), magnesia (MgO) and alumina (Al_2O_3) content of the rock, and determining where the composition of the rock falls on a plot of CaO/MgO ratio versus the Al_2O_3 content, as shown in Figure 3. If the composition falls in the range of "aggregates considered to be potentially expansive," the aggregate is potentially alkali-carbonate reactive. Such aggregates must be tested using the ASTM C 1293 (concrete prism test) as ASTM C 1260 (accelerated mortar bar test) is not suitable for detecting alkali-carbonate reaction.

[2]CSA is the Canadian Standards Association. CSA Standards such as A23.2 Method of Test and Standard Practices for Concrete can be found at www.csa.ca

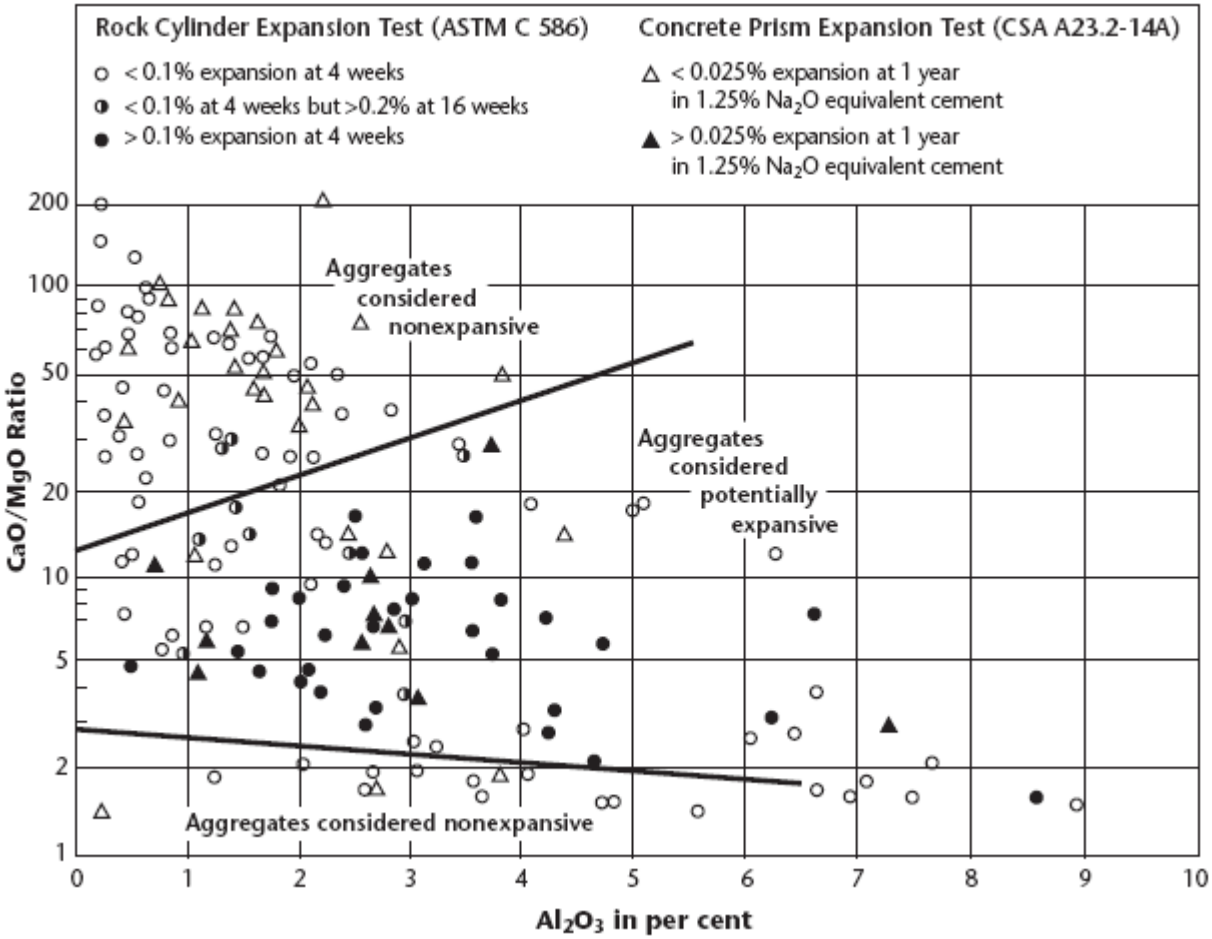

Figure 3. Using Chemical Composition as a Basis for Determining Potential Alkali-Carbonate Reactivity of Quarried Carbonates (from CSA A23.2-26A)

3.4. Accelerated Mortar Bar Test, ASTM C 1260

If the aggregate is not a quarried carbonate or it is a quarried carbonate with a composition that falls outside of the region of "aggregates considered to be potentially reactive" in Figure 3 when tested in accordance with CSA A23.2-26A, the next step is to test the aggregate in accordance with ASTM C 1260.

Coarse aggregates for this test have to the crushed to sand size (< 5 mm) and then washed and graded to meet the grading requirements of the test. Sands have to be washed and graded to meet the same grading requirements. The test is intended to evaluate coarse and fine aggregates separately, and should not be used to evaluate job combinations of coarse and fine aggregates.

In this test, mortar bars are produced with the aggregate being evaluated and at the age of two days the bars are immersed into a solution of 1 M NaOH maintained at a temperature of 176oF (80oC) and the length change of the bars is monitored. If the mortars do not expand by more than 0.10% after 14 days immersion in this solution, the aggregate is considered non-deleteriously reactive. If the mortar bar expands by more that 0.10% at 14 days, the aggregate is considered to be potentially reactivity and its reactive should be confirmed in ASTM C 1293 (concrete prism test).

3.5. Concrete Prism Test, ASTM C 1293

The concrete prism test is suitable for evaluating all aggregate types and is considered to be the most reliable laboratory test for predicting field performance of aggregates. If the aggregate being tested is a coarse aggregate it is blended with a non-reactive fine aggregate and vice-versa, and the coarse-fine aggregate combination is used to produce concrete prisms with a specified high alkali loading. The test is not intended for use with specific job combinations of coarse and fine aggregate, however, it is generally considered acceptable to do this, but the results are not applicable if either the coarse or fine aggregate is changed during the job.

The prisms are stored over water in sealed containers at 100oF (38oC) and the length change is monitored periodically. If the prisms do not expand by more than 0.04% after 1 year, the aggregate is considered non-deleteriously reactive and may be used in concrete with no further testing (for AAR). If the prism expands by more that 0.04% at 1 year, the aggregate is considered to be potentially reactive and preventive measures are required if the aggregate is to be used in concrete construction.

If the aggregate tested was a quarried carbonate rock with a chemical composition that fell within the region of "aggregates considered to be potentially reactive," the concrete prisms must be examined to determine whether alkali-carbonate reaction contributed to the expansion.[3] If damaging ACR is detected, either in isolation or in combination with ASR, the rock should not be used in concrete without selective quarrying or aggregate beneficiation to remove the reactive components.

3.6. Interpretation of Results from Laboratory Tests

Figure 2 shows dotted lines from the boxes marked "Field History", "Petrographic Examination", and "Accelerated Mortar Bar Test" to the box marked "Non-Reactive" as there is an element of risk associated with accepting aggregates solely on the basis of these tests. With field history it is usually difficult to firmly establish that the materials and conditions to be used in a new project are the same as those used in a structure that is more than 10 to 15 years old. With some aggregates it may not be possible to identify reactive constituents by petrographic examination.

The accelerated mortar bar test (AMBT) is generally recognized as a relatively severe test and it is well established that it identifies as deleteriously reactive many aggregate sources that have a history of satisfactory field performance and that perform well in the concrete prism test (CPT);[4] that is the CPT identifies the same aggregate as non-deleteriously reactive. For this reason, results from the accelerated mortar bar test should not be used to reject an aggregate. If an aggregate fails the AMBT (expansion > 0.10% at 14 days) its reactivity should be confirmed by testing using the CPT. If the results of the AMBT and CPT are in disagreement, the results of the CPT shall prevail.

[3]The determination of the extent to which the alkali-carbonate reaction contributed to the expansion of the concrete should be conducted by an expert with experience of ACR. Methods used might include a petrographic examination of the concrete (ASTM C 856), accelerated microbar testing of the aggregate (Lu et al., 2004), and/or rock cylinder expansion tests (ASTM C 586) conducted on samples of rock from the quarry. The ASTM C 1105 version of the concrete prism test for alkali-carbonate rock reaction may also be used but the alkali content of the concrete should be kept sufficiently low to ensure that expansion due to alkali-silica reaction is eliminated during the test. Keeping the alkali content below 1.8 kg/m^3 (3.0 lb/yd^3) Na_2Oe should be sufficient for this purpose.

[4]The term "false positive" is used to describe the case where a test method incorrectly identifies an aggregate as deleteriously reactive. Similarly, "false negative" describes the case where a test wrongly identifies an aggregate as being non-deleteriously reactive.

Until recently it was assumed that aggregates that passed the AMBT (expansion ≤ 0.10% at 14 days) were most likely to pass the CPT (expansion ≤ 0.04% at 1 year), and such aggregates could be accepted for use in concrete without the need for confirmatory testing using the CPT. However, there appears to be an increasing number of coarse aggregates that pass the AMBT and fail the CPT (Folliard et al. 2006) and this is somewhat disconcerting for specifications that permit the use of aggregates passing the AMBT with no further testing (that is no requirements for CPT). [5] Consequently, there is a risk associated with accepting an aggregate solely on the basis of the results from the AMBT.

In Figure 2, the AMBT is shown with a broken line as there is the possibility of incorrectly identifying a deleteriously-reactive aggregate as being non-deleteriously-reactive using this test method. The most reliable approach for determining aggregate reactivity is to use the CPT as the expansion test for all cases (that is to exclude the AMBT from the evaluation process). However, it is recognized that the long duration of the CPT makes it impractical for use in many circumstances and there is a need for a more rapid test. Despite its limitations, the AMBT is probably the most viable accelerated test currently in use.

3.7. Risk Evaluation

The risk of AAR-damage occurring due to a failure to detect deleteriously reactive aggregate can be reduced by implementing routine testing using petrography and/or laboratory expansion tests. Increasing the complexity and frequency of testing will result in lower risks but higher costs. For example, frequent petrographic and concrete prism testing of all aggregate sources may reduce the risk of failing to identify deleteriously reactive aggregates to a negligible level, but the costs associated with this level of testing may not be justified in a region where there are few cases of AAR and where most aggregate sources have a good field performance history. It is incumbent on the owner to define what level of risk is acceptable and thus determine the type and frequency of testing.

3.8. Other Test Methods

There are many other test methods for evaluating the reactivity of aggregates and a full discussion of these tests is beyond the scope of this report. One of the more promising tests is an accelerated version of the CPT, which is conducted at 140oF (60oC) to accelerate the reaction. A detailed discussion of these tests can be found elsewhere (Thomas et al. 2006).

4.0 Preventing Damaging Expansion in Concrete Containing Alkali-Silica Reactive Aggregates

This report provides two approaches for selecting preventive measures. In the first approach, the performance of the preventive measure is tested in combination with the reactive aggregate using either

[5] It has been proposed to extend the duration of this test and to use an expansion limit of 0.10%, or even, 0.08% after 28 days immersion in 1 M NaOH at 176 °F (80 °C). This more onerous requirement should be adopted only when it can be demonstrated that extension of the test period is required to capture aggregates that have been identified as being deleteriously reactive either by concrete prism testing or field performance. The extended test duration should not be applied across the board to all aggregates as this will result in an unacceptable number of cases where the accelerated mortar bar test results in false positives (that is the test wrongly identifies aggregates as deleteriously reactive). It should be noted that extending the test duration does not capture all of the aggregates that have been found to pass the AMBT but fail the CPT.

the CPT or the AMBT. This approach is suitable for selecting the appropriate level of SCM's or lithium nitrate admixtures. The second is a prescriptive approach where the preventive measure is selected on the basis of the reactivity of the aggregate, the nature of structure and its exposure, the required service life, and the availability of alkalis in the system. This approach is suitable for selecting the appropriate level of SCM and/or the maximum alkali content of the concrete.

The preventive measures determined by either performance testing or prescription using this report will generally reduce the risk of expansion due to ASR to an acceptable level for most highway applications. However, it should be noted that the level of prevention arrived at by following this report may not be sufficient for certain critical structures such as hydraulic dams or power plants where ASR expansion of any level cannot be tolerated.

4.1. Performance Testing Using the Concrete Prism Test (CPT)

The ability of SCM's such as fly ash, slag, silica fume and natural pozzolans, or of chemical admixtures, such as lithium compounds, to control deleterious expansion with a reactive aggregate can be evaluated using a modified version of the concrete prism test, ASTM C 1293. When testing SCM's, the total cementitious content is maintained at 708 lb/yd^3 (420 kg/m^3), but the portland cement is partially replaced with the desired amount of the SCM (or combination of SCM's) under investigation. The alkali content of the portland cement component of the mix only is raised to 1.25% Na2Oe.[6] It is prudent to conduct a number of tests using varying levels of SCM(s) to optimize the proportions in terms of meeting the expansion criteria. The test duration for evaluating preventive measures is two years and the expansion criterion used to demonstrate that the combination of SCM and reactive aggregate is suitable for use in concrete construction is expansion $\leq 0.04\%$ at 2 years.

The only lithium compound included in this report is an aqueous solution of lithium nitrate.[7] When testing lithium nitrate solution the procedure in ASTM C 1293 is followed with the following exceptions:

- The alkali content of the portland cement is raised to 1.25% Na_2Oe.
- The desired quantity of lithium nitrate solution is added to the mix water prior to mixing. It is prudent to conduct a number of tests using varying amounts of lithium to determine the minimum "safe" level required to sufficiently suppress expansion.[8]
- The amount of water contained in the lithium nitrate solution should be included in the calculation of W/CM. In other words, this amount of water should be subtracted from the mix water content required for the same mix without lithium.

[6]The expansion of concrete prisms produced with cement alkalis raised to 1.25% Na_2Oe provides a reliable prediction of the field expansion of concrete produced with cement with alkalis up to 1.0% Na_2Oe. If the cement to be used in the field has an alkali content above 1.00% Na_2Oe, this same cement should be used for the concrete prism test and the alkalis should be raised by 0.25% Na_2Oe by the addition of NaOH to the mix water.

[7]At the time of writing, the only commercially available products were all solutions containing 30% $LiNO_3$.

[8]The published literature indicates that the level of lithium required increases as the concentration of the other alkalis (Na+K) in the system increases. For many aggregates, deleterious expansion appears to be prevented when the lithium-to-sodium-plus-potassium-molar ratio, [Li]/ [Na+K] ≥ 0.74. For a 30%-solution of $LiNO_3$, the molar ratio of 0.74 is achieved when the dose of lithium is equal to 0.55 gal LiNO3 solution per lb Na2Oe (4.6 L $LiNO_3$ solution per kg Na2Oe). The alkalis added to the mix water as NaOH should be included in the calculation of the lithium-to-sodium-plus-potassium-molar ratio.

- The test is extended to two years and the expansion criterion used to demonstrate that the combination of lithium and reactive aggregate is suitable for use in concrete construction is expansion ≤ 0.04% at 2 years.

4.2. Performance Testing Using the Accelerated Mortar Bar Test (AMBT)

Before the accelerated mortar bar test (AMBT) can be used to determine the performance of a specific SCM-aggregate or lithium-aggregate combination, it must first be demonstrated that the aggregate being evaluated responds well to the accelerated test. This requires a comparison of the results from the AMBT and the CPT test for the aggregate being used (without preventive measures). After subjecting the aggregate to both tests, the results are plotted on Figure 4. Provided the data fall within the region indicated in Figure 4, the AMBT can be used to determine the efficacy of both SCM's and lithium nitrate. The AMBT and CPT should be compared every two years unless the results of petrography or other tests indicate a significant change in the composition of the material in the quarry, in which case new tests should be commenced immediately.

When testing the SCM in the AMBT, the modified version of the test, ASTM C 1567, should be used; this test was developed specifically for "determining the potential alkali-silica reactivity of combinations of cementitious materials and aggregates." Combinations of cementitious materials and aggregates will be deemed acceptable for use if the expansion ≤ 0.10% after 14 days immersion in 1 M NaOH.[9] Note: this test method is not suitable for evaluating SCM's with high levels of alkalis (fly ash with > 4.5% Na_2Oe, and slag and silica fume with > 1.0% Na_2Oe) and such materials should be evaluated using the concrete prism test.

[9]If it has been determined that an extended test duration of 28 days in 1M NaOH and a lower expansion limit of 0.08% is required to correctly identify the aggregate as deleteriously reactive then the same requirements should be used to evaluate the preventive measures.

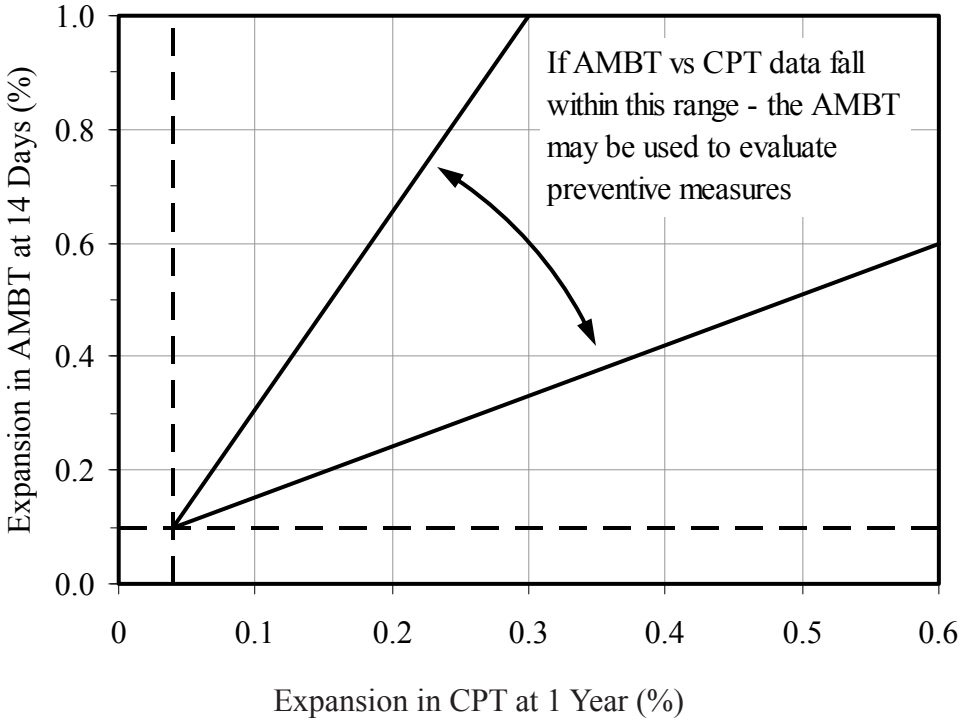

Figure 4. Comparison of AMBT and CPT Data for the Purpose of Determining Whether the AMBT is Suitable for Evaluating Preventive Measures with a Specific Aggregate

When using the AMBT to determine the lithium dose required with a specific aggregate the approach proposed by Tremblay et al. (2008) will be used; the procedure is as follows:

1. Test the aggregate using the standard AMBT (ASTM C 1260). Extend the duration of the test such that the mortar bars are exposed to 1M NaOH at 80oC (178oF) for a period of 28 days. Let E1 = expansion of bars without lithium at 28 days.

2. Test the aggregate in a modified version of the AMBT. In this test add sufficient lithium nitrate to the mortar bar mixture and the soak solution to achieve lithium-to-alkali molar ratios of [Li]/ [Na+K] = 0.74 in the mortar and [Li]/ [Na+K] = 0.148 in the soak solution. Conduct the rest of the test in accordance with ASTM C 1260 extending the period in 1 M NaOH to 28 days. Let E2 = expansion of bars with lithium at 28 days.

3. If $(E_2 - E_1)/E_1 < 0.1$ then use the following lithium-to-alkali molar ratio:

(Eq.1)

$$LA=[LI]/[Na + K] = 1.0 + 0.7X [(E_2 - E_1)/E_1]$$

Where LA is the lithium-to-sodium-plus-potassium molar ratio. The amount of 30%-$LiNO_3$ solution required in the concrete mix is then 0.55 x LA/0.74 gal of lithium solution per lb of Na_2Oe in the concrete mixture (or 4.6 x LA/0.74 liters of lithium solution per kg of Na_2Oe.

4. If $(E_2 - E_1)/E_1 \geq 0.1$ then use the concrete prism test to determine the lithium content required (see Section 5.2).

4.3. Prescriptive Approach for Selecting Preventive Measures

The level of prevention is determined by considering the class, size and exposure condition of the structure, the degree of aggregate reactivity, and the level of alkalis from the portland cement (when SCM's are used as preventive measures). This approach is similar to that developed in Canada (CSA A23.2-27A) and in Europe (RILEM TC191-ARP: AAR-7).

4.3.1. Degree of Aggregate Reactivity

The degree of alkali-silica reactivity of an aggregate is determined by testing the aggregate in the CPT and using the expansion value at one-year. Aggregate-reactivity classes are given in Table 1.

Table 1. Classification of Aggregate Reactivity

Aggregate-Reactivity Class	Description of Aggregate Reactivity	One-Year Expansion in CPT (%)
R0	Non-reactive	< 0.040
R1	Moderately reactive	0.040 - 0.120
R2	Highly reactive	0.120 - 0.240
R3	Very highly reactive	> 0.240

If data from the CPT are not available, the aggregate may be considered as very highly reactive (R3).

Where the coarse and fine aggregates are of different reactivity, the level of prevention should be selected for the most reactive aggregate.

4.3.2. Level of ASR Risk

The risk of ASR occurring in a structure is determined by considering the aggregate reactivity and the exposure conditions using Table 2.

Table 2. Determining the Level of ASR Risk

Size and exposure conditions	Aggregate-Reactivity Class			
	R0	R1	R2	R3
Non-massive† concrete in a dry[2] environment	Level 1	Level 1	Level 2	Level 3
Massive† elements in a dry†† environment	Level 1	Level 2	Level 3	Level 4
All concrete exposed to humid air, buried or immersed	Level 1	Level 3	Level 4	Level 5
All concrete exposed to alkalis in service†††	Level 1	Level 4	Level 5	Level 6

†A massive element has a least dimension > 3 ft (0.9 m)

††A dry environment corresponds to an average ambient relative humidity lower than 60%, normally only found in buildings

†††Examples of structures exposed to alkalis in service include marine structures exposed to seawater and highway structures exposed to deicing salts (e.g. NaCl) or anti-icing salts (e.g. potassium acetate, sodium formate, etc.)

4.3.3. Determination of the Level of Prevention

The level of prevention required is determined from Table 3 by considering the risk of ASR from Table 2 together with the class of structure from Table 4.

Table 3. Determining the Level of Prevention

Level of ASR Risk (Table 4)	Classification of Structure (Table 4)			
	S1	S2	S3	S4
Risk Level 1	V	V	V	V
Risk Level 2	V	V	W	X
Risk Level 3	V	W	X	Y
Risk Level 4	W	X	Y	Z
Risk Level 5	X	Y	Z	ZZ
Risk Level 6	Y	Z	ZZ	††

††It is not permitted to construct a Class S4 structure (see Table 4) when the risk of ASR is Level 6. Measures must be taken to reduce the level of risk in these circumstances.

Table 4. Structures Classified on the Basis of the Severity of the Consequences Should ASR[†] Occur (Modified for Highway Structures from RILEM TC 191-ARP)

Class	Consequences of ASR	Acceptability of ASR	Examples[††]
S1	Safety, economic or environmental consequences small or negligible	Some deterioration from ASR may be tolerated	▪ Non-load-bearing elements inside buildings ▪ Temporary structures (e.g. < 5 years)
S2	Some safety, economic or environmental consequences if major deterioration	Moderate risk of ASR is acceptable	▪ Sidewalks, curbs and gutters ▪ Service-life < 40 years
S3	Significant safety, economic or environmental consequences if minor damage	Minor risk of ASR acceptable	▪ Pavements ▪ Culverts ▪ Highway barriers ▪ Rural, low-volume bridges ▪ Large numbers of precast elements where economic costs of replacement are severe ▪ Service life normally 40 to 75 years
S4	Serious safety, economic or environmental consequences if minor damage	ASR cannot be tolerated	▪ Major bridges ▪ Tunnels ▪ Critical elements that are very difficult to inspect or repair ▪ Service life normally > 75 years

[†]Note: this table does not consider the consequences of damage due to ACR. This protocol does not permit the use of alkali-carbonate aggregates

[††]The types of structures listed under each Class are meant to serve as examples. Some owners may decide to use their own classification system. For example, sidewalks and culverts may be placed in the S3 Class is some jurisdictions.

4.3.4. Identification of Preventive Measures

Option 1 – Limiting the Alkali Content of the Concrete

Damaging alkali-silica reaction can be prevented by limiting the alkali content of the concrete. Maximum permissible alkali contents are given in Table 5. The alkali content of concrete is calculated on the basis of the alkali contributed by the portland cement alone.

Table 5. Maximum Alkali Contents to Provide Various Levels of Prevention

Prevention Level	Maximum alkali content of concrete (Na_2Oe)	
	lb/yd^3	kg/m^3
V	No limit	
W	5.0	3.0
X	4.0	2.4
Y	3.0	1.8
Z†	Table 7	
ZZ†		

†SCM's must be used in Prevention levels Z and ZZ.

Option 2 – Using Supplementary Cementing Materials (SCM)

Damaging alkali-silica reaction can be prevented by using a sufficient quantity of a suitable supplementary cementing material (SCM) such as fly ash, slag, silica fume or natural pozzolan. Table 6 provides minimum replacement levels for Class F fly ash with less than 18% CaO and meeting the requirements of ASTM C 618, silica fume with more than 85% SiO_2 and meeting the requirements of ASTM C 1240, and slag meeting the requirements of ASTM C 989. Class C fly ashes or Class F fly ashes with more than 18% CaO are not covered by these prescriptive measures; the ability of these materials to control ASR with a particular reactive aggregate should be determined by performance testing (see sections 4.1 and 4.2).

Many natural pozzolans such as metakaolin, calcined clays and shales, and volcanic ash have been shown to be effective in controlling expansion due to ASR. However, no prescriptive measures are provided for natural pozzolans in Table 6 as this class of materials covers a wide variety of pozzolan types with a broad range of properties. When natural pozzolans are to be used to control ASR, the efficacy of a particular aggregate-pozzolan combination should be determined by performance testing (see sections 4.1 and 4.2). Information on natural pozzolans can be found in ACI 232.1R Use of Raw or Processed Natural Pozzolans in Concrete.

Table 6. Minimum Levels of SCM to Provide Various Levels of Prevention

Type of SCM	Alkali level of SCM (% Na_2Oe)	Minimum Replacement Level†† (% by mass)				
		Level W	Level X	Level Y	Level Z	Level ZZ
Fly ash (CaO ≤ 18%)	< 3.0	15	20	25	35	Table 7
	3.0 – 4.5	20	25	30	40	
Slag	< 1.0	25	35	50	65	
Silica Fume† (SiO_2 > 85%)	< 1.0	1.2 x LBA or 2.0 x KGA	1.5 x LBA or 2.5 x KGA	1.8 x LBA or 3.0 x KGA	2.4 x LBA or 4.0 x KGA	

†The minimum level of silica fume (as a percentage of cementing material) is calculated on the basis of the alkali (Na_2Oe) content of the concrete contributed by the portland cement and expressed in either units of lb/yd^3 (LBA in Table 6) or kg/m^3 (KGA in Table 6). LBA is calculated by multiplying the cement content of the concrete in lb/yd^3 by the alkali content of the cement divided by 100. For example, for a concrete containing 500 lb/yd^3 of cement with an alkali content of 0.81% Na_2Oe the value of LBA = 500 x 0.81/100 = 4.05 lb/yd^3. For this concrete, the minimum replacement level of silica fume for Level Y is 1.8 x 4.05 = 8.1%. KGA is calculated by multiplying the cement content of the concrete in kg/m^3 by the alkali content of the cement divided by 100. For example, for a concrete containing 300 kg/m^3 of cement with an alkali content of 0.91% Na_2Oe the value of KGA = 300 x 0.91/100 = 2.73 kg/m^3. For this concrete, the minimum replacement level of silica fume for Level X is 2.5 x 2.73 = 6.8%. Regardless of the calculated value, the minimum level of silica fume shall not be less than 7% when it is the only method of prevention.

†† Note: the use of high levels of SCM in concrete may increase the risk of problems due to deicer salt scaling if the concrete is not properly proportioned, finished and cured.

When two or more SCM's are used together to control ASR, the minimum replacement levels given in Table 6 for the individual SCM's may be reduced provided that the sum of the parts of each SCM is greater than or equal to one. For example, when silica fume and slag are used together, the silica fume level may be reduced to one-third of the minimum silica fume level given in the table provided that the slag level is at least two-thirds of the minimum slag level.

The minimum replacement levels in Table 6 are appropriate for use with portland cements of moderate to high alkali contents (0.7 to 1.0 % Na_2Oe). Table 7 provided recommendations for adjusting the level of SCM when the alkali content of the portland cement is above or below this range. Where SCM's are combined with lower alkali cements (< 0.7% Na_2Oe) it is probably safe to adopt the value of the minimum replacement level for the next prevention level down. For example, if slag is to be used in prevention level Y with a low-alkali cement, the level of slag can be reduced to the level specified for prevention level X (35%). The replacement levels should not be below those given in Table 6 for prevention level W, regardless of the alkali content of the portland cement. Similarly, if higher alkali cements (> 1.0% Na_2Oe) are used together with SCMs, the replacement level of SCM should be increased to that required for the next prevention level up. For example, if slag is to be used in prevention level Y with a high-alkali cement, the level of slag should be increased to the level specified for prevention level Z (65%). This report does not provide guidance for using preventive measures with reactive aggregates when the alkali content of the portland cement exceeds 1.25% Na_2Oe.

Table 7. Adjusting the Minimum Level of SCM Based on the Alkali Content of the Portland Cement

Cement Alkalis (% Na_2Oe)	Level of SCM
< 0.70	Reduce the minimum amount of SCM given in Table 6 by one prevention level†
0.70 to 1.00	Use the minimum levels of SCM given in Table 6
> 1.00	Increase the minimum amount of SCM given in Table 6 by one prevention level
> 1.25	No guidance is given

†The replacement levels should not be below those given in Table 6 for prevention level W, regardless of the alkali content of the portland cement.

Option 3 – Controlling the Alkali Level of Concrete and using SCMs when Exceptional Levels of Prevention are Required (Levels Z and ZZ)

Where extreme levels of prevention are required, a combination of Options 1 and 2 may be required. This approach requires that a minimum level of SCM is used and that a maximum limit is placed on the alkali content of the concrete contributed by the portland cement. Options for Prevention Levels Z and ZZ are given in Table 8.

Table 8. Using SCM and Limiting the Alkali Content of the Concrete to Provide Exceptional Levels of Prevention

Prevention Level	SCM as sole prevention	Limiting concrete alkali content plus SCM	
	Minimum SCM level	Maximum alkali content, lb/yd^3 (kg/m^3)	Minimum SCM level
Z	SCM level shown for Level Z in Table 7	3.0 (1.8)	SCM level shown for Level Y in Table 6
ZZ	Not permitted	3.0 (1.8)	SCM level shown for Level Z in Table 6

5.0 SUMMARY

This document describes a report for determining the reactivity of concrete aggregates and selecting appropriate measures for preventing deleterious expansion in new concrete construction. It is recommended that the following sequence of testing is followed to determine aggregate reactivity: consideration of field performance history, petrographic examination, accelerated mortar bar testing and concrete prism testing. Some agencies may adopt one or more of these test procedures depending on prior experience with ASR and the acceptable level of risk of ASR in new construction. Appropriate preventive measures can be selected either by performance testing using the accelerated mortar bar test or concrete prism test, or by using prescribed measures which have been developed based on previous experience and published research data. The level of prevention prescribed is a function of the class of the structure, the reactivity of the aggregate, the alkali content of the portland cement, the composition of the material used for prevention, and the exposure conditions. This report is not aimed at completely eliminating the possibility of ASR expansion occurring in new construction but it does provide various approaches for minimizing the risk of ASR to a level acceptable to the owner.

6.0 REFERENCES

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