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# Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete

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## Abstract

This paper provides a critical evaluation of the various methods available for testing the efficacy of measures for preventing expansion due to alkali–silica reaction (ASR) in concrete containing deleteriously reactive aggregate. The ideal test method should be rapid, reliable and capable of determining the influence of aggregate reactivity, alkali availability and exposure conditions. None of the currently available or commonly used methods meet all of these criteria. The shortcomings of the different test methods are discussed and suggestions are made for modifying the concrete prism test and accelerated mortar bar test to make these tests more acceptable.

*Keywords:* Alkali-silica reaction; Reactive aggregate

## 1. Introduction

In 1940, Thomas Stanton of the California State Division of Highways published the first paper [1] on alkali–silica reaction (ASR). In addition to describing the nature of the reaction in this paper, Stanton also presented findings demonstrating that deleterious reaction could be prevented by using low-alkali cement, which he defined as having an alkali content below 0.60% $Na_2Oe$, or by incorporating pumicite (a pozzolan) in the mixture. In the following decade, Stanton confirmed the ameliorative effect of a wider range of pozzolans [2] and research from other workers demonstrated the efficacy of other supplementary cementing materials such as fly ash [3] and slag [3,4], and certain chemical compounds such as lithium [5]. In the 50 years since these findings were published, there have been literally hundreds of publications reporting results from studies on the prevention of ASR expansion. The findings from these studies can be summarized as follows [6–10]:

- Most, if not all, supplementary cementing materials (SCMs) can be used to prevent damaging reaction due to ASR provided they are used in sufficient quantity. The quantity required is primarily a function of (i) the composition of the SCM (particularly its CaO, $SiO_2$ and $Na_2Oe$ content), (ii) the nature and the level of reactivity of the aggregate (different aggregates require different levels of SCM), and (iii) the alkali content provided by the portland cement (and other sources such as aggregates and chemical admixtures).
- Lithium can be used to suppress expansion with most, if not all, reactive aggregates provided the lithium-to-alkali ratio, $Li/(Na+K)$, is sufficient. The ratio required is primarily a function of (i) the form of lithium used and (ii) the nature of the reactive aggregate.
- Restricting the alkali contribution from the portland cement component of the concrete can be effective in controlling ASR expansion. The maximum alkali content that can be tolerated in the concrete without causing damaging expansion is a function of the reactive aggregate type. Consideration must be given to the availability from other sources both within (e.g. aggregates) and external to (e.g. deicing salts) the concrete.

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Determining the "safe" level of SCM, lithium or cement alkalis for a particular type of reactive aggregate requires access to a suitable performance test. Although numerous test methods are available, they vary considerably in terms of their reliability and the resources and time required for running the test. At this time, there is no laboratory test suitable for evaluating the risk of expansion with the specific combination of materials intended for a particular job, as most test methods require the augmentation of the alkali level (by boosting the alkali loading within the mixture or relying on a highly alkaline soak solution) to ensure that the aggregate reacts under laboratory conditions and in a reasonable period of time. This paper discusses the various test methods available and their applicability for assessing the different approaches for preventing deleterious expansion. Suggestions are made for modifying existing test methods for evaluating job mixtures.

## 2. Research significance

Currently, there are a number of test methods used to evaluate the efficiency of pozzolans, slag or lithium-based admixtures in terms of controlling expansion due to alkali–silica reaction (ASR). The test conditions used vary widely from one test to another and different tests often produce different results with regards to determining the minimum "safe" level of pozzolan, slag or lithium compound required to prevent expansion. This paper provides a critical evaluation of the different test methods and makes recommendations for improving two of these tests.

## 3. Procedures for evaluating preventive measures

### 3.1. Evaluating performance in concrete structures

Using existing field performance is a valid approach for assessing the potential for an aggregate to produce damaging ASR. Indeed, it has been claimed that field service is "possibly the best method" [11] or even "the most reliable means" [12] for this purpose. Many specifications (e.g. [13]) or guidelines allow the acceptance of an aggregate based solely on field performance although proper attention must be paid to determine the age of the structures being evaluated (e.g. must be at least 10 years old), the alkali loading in the concrete (should not be exceeded in future construction), and the presence of SCM.

Field performance can also be used to evaluate the efficacy of preventive measures where they have been used with known reactive aggregates to build a concrete structure. For example, if there is a sufficient number of structures available, it may be possible to develop a relationship between the alkali content of the concrete and the degree of ASR damage to determine the threshold alkali content below which deleterious ASR does not occur. This is certainly the most reliable method of determining the safe alkali level for a particular aggregate, but there are rarely enough structures, adequate records and sufficient resources available to make such a determination.

The field performance of concrete structures has been used to demonstrate the effectiveness of fly ash, slag and silica fume in controlling damaging ASR [6,7]. Unfortunately, there are insufficient data available from the field to allow the interaction of all the influencing parameters to be studied. For example, for a given aggregate how does the minimum level of fly ash required to suppress expansion vary with the composition of the fly ash and the content of alkali supplied by the portland cement? This cannot be answered from existing field service records despite the extensive use of fly ash around the world in the last 5 decades. However, field performance data can be used to underpin prescriptive specifications or provide benchmarks for performance tests.

There are few documented cases where an SCM has been used in conjunction with a high-alkali cement and a known reactive aggregate. One such example is the Lower Notch Dam in Ontario, Canada, which was completed in 1971. The concrete for the dam utilized a highly reactive greywacke-argillite coarse aggregate and high-alkali cement (1.08% $Na_2Oe$) in combination with 20% and 30% low-CaO fly ash in the structural and mass concrete, respectively [14]. Similar reactive aggregates have been implicated in numerous ASR-affected highway and hydraulic structures in the same geographic area [15]. The fly ash concrete has performed well with no indications of ASR damage after more than 30 years of service. This fact provides confidence in the current prescriptive specifications in Canada [13], which require a minimum of 15% to 25% Type F fly ash (<8% CaO) depending on the reactivity of the aggregate, the severity of the exposure condition and the required service life of the structure. If the same dam was built today with the same reactive aggregate, the existing specification would call for a minimum of 25% of the type of fly ash used. The performance of the Lower Notch Dam substantiates the specified prescriptive measure.

The field performance of structures built using similar reactive aggregates played a crucial role in the development of the Canadian concrete prism test, Test Method CSA A23.2-14A, which has since been adopted by ASTM, as Test Method C 1293. These known reactive aggregates are not identified as being reactive by some conventional tests, such as the mortar bar test (ASTM C 227) or earlier versions of the concrete prism test with 310 $kg/m^3$ of cement. The cement content of the concrete prism test was raised to its current value of 420 $kg/m^3$ (708 $lb/yard^3$) of high-alkali cement (boosted to 1.25% $Na_2Oe$ by the addition of NaOH) to capture these and similar reactive rock types [15,16].

A database of field performance records for a wide range of materials would be an invaluable aid for the development and further improvement of specifications and test methods. The data required include information on composition and proportions used in the production of the concrete, methods of construction, exposure conditions and some measure of performance. Such records are required for structures that are at least 10 years old. Obviously, comprehensive data of this type are rarely available.

### 3.2. Field exposure of large concrete blocks

Monitoring large blocks stored on an external exposure site provides a good surrogate for field service records. An example

Fig. 1. View of one of the exposure sites at BRE.

of exposure site studies is the site at the Building Research Establishment (BRE) in the U.K. where large elements ranging in size from 350-mm to 900-mm (13.8-in. to 35.4-in.) cubes are stored directly on the ground or ponded in water such that 25 to 50 mm (1 to 2 in.) of the bottom of the sample is immersed; see Fig. 1. Field exposure of large blocks has been used to supplement laboratory studies on the use of fly ash, slag, metakaolin and lithium compounds to control ASR. Expansion measurements can be made easily using DEMEC-type strain gauges and embedded reference points. Expansion data for 10 sets of points on a 900-mm (35.4-in.) cube on the BRE exposure site are shown in Fig. 2. This concrete contains 475 kg/m$^3$ (801 lb/yard$^3$) of a high-alkali cement (1.15% $Na_2Oe$) with a reactive flint sand representing 25% of the total aggregate, which is the pessimum level for this sand [17]. There is a wide scatter between data from different reference points and this is a result of variations in exposure due to orientation with regards the sun and prevailing wind (rain) and height above the water supplied to the base of the sample. This necessitates the installation of a range of reference points to achieve a meaningful average for the block.

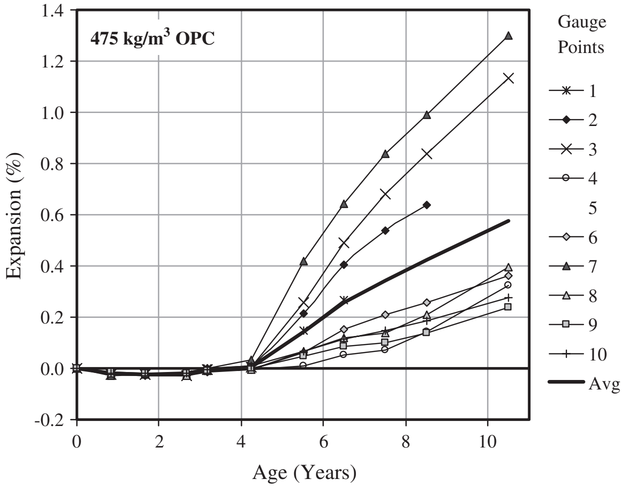

Fig. 2. Expansion data for 900-mm cube (with flint sand) on BRE exposure site.

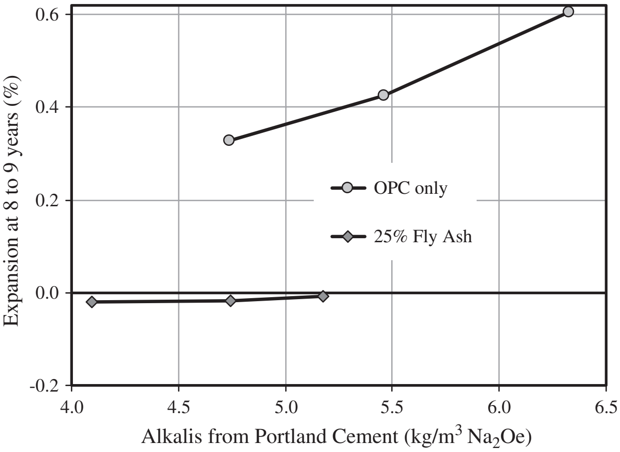

Fig. 3. Effect of fly ash on expansion of 900-mm concrete cubes (with flint sand).

Fig. 3 shows the latest available expansion data (1998) plotted against the alkali content of the concrete calculated on the basis of the alkalis contributed from the portland cement component of the mix only. The impact of using a low-calcium fly ash at 25% by mass of the total cementing material can be seen clearly from these data and from the photograph of 11-year-old specimens in Fig. 4. The beneficial effect of the fly ash extends beyond that of a mere diluent as fly ash controls expansion even when the contribution of alkalis from the Portland cement is sufficient to produce excessive expansion and cracking in concrete without SCM. These observations from field exposure studies confirm the findings from laboratory studies [17] and provide confidence in the specifications developed on the basis of both the laboratory and field data (e.g. [18]).

Comprehensive field exposure studies are currently being conducted at the University of Texas in Austin [19] and CANMET in Ottawa [20,21]; these sites are shown in Fig. 5. These studies include the evaluation of preventive measures based on SCM and lithium-based compounds (including combinations thereof), the use of low-alkali cements, and the combined effects of ASR and delayed ettringite formation (DEF) in heat-cured concrete. Large blocks from selected parallel mixes have been placed on both sites and in the tidal zone of a marine exposure site at Treat Island, Maine, to examine the influence of climate and exposure conditions. These studies are currently being extended to look at various technologies for suppressing expansion in existing ASR-affected concrete.

### *3.3. Concrete prism expansion tests (ASTM C 1293 and CSA A23.2-14A)*

There are a number of different concrete prism tests used to identify reactive aggregates or evaluate preventive measures, but most of them are similar to the extent that elevated temperature and augmented cement alkalis are used to accelerate the reaction.

The development of the Canadian concrete prism test (now CSA A23.2-14A) began in the 1950s [22], the principal motivation being the failure of the standard mortar bar test (ASTM C 227) to correctly identify both alkali–silica [23] and

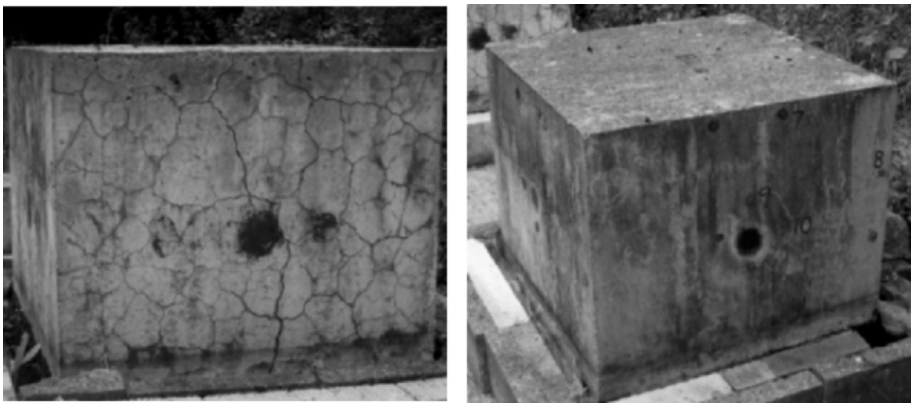

Fig. 4. Photographs of 900-mm cubes of 11-year-old concrete with 100% OPC (left) and with 25% fly ash (right).

alkali–carbonate [24] reactive rocks in Ontario. Originally, concrete prisms containing 310 kg/m$^3$ (523 lb/yard$^3$) of cement were stored in a moist-curing room at 23 °C (73 °F) and an expansion limit of 0.020% at 84 days was used to indicate potentially reactive aggregates. The test has been continuously calibrated against field performance over the years, and the test conditions have evolved to ensure that all known reactive aggregates are correctly identified [15]. The current version of the test, first published in 1994, uses a cement content of 420 kg/m$^3$ (708 lb/yard$^3$) with the cement alkalis raised to 1.25% Na$_2$Oe by the addition of NaOH to the mix water, and concrete prisms (75 mm × 75 mm in cross-section × 275 mm to 405 mm in length, 3 in. × 3 in. × 11 in. to 16 in.) are stored over water in sealed containers at 38 °C (100 °F). The test limit used is an expansion limit of 0.040% at 1 year to identify reactive aggregates and the same limit at 2 years to qualify preventive measures. The test method in its current form was adopted by ASTM in 1995 (as ASTM C 1293).

To the authors' knowledge there are no aggregates that pass the current test conditions and performance limits that have caused damaging alkali–silica or alkali–carbonate reaction in concrete structures. It has been suggested that the test conditions are too severe as some aggregates with generally good field performance may be identified as being potentially reactive by the concrete prism test [25]. However, it has been acknowledged that these same aggregates may cause deleterious reaction if they are in concrete with higher alkali contents, such as the types of concrete commonly used nowadays in highway structures, which are often characterized by having relative high cement contents [25].

Experience has shown that a higher level of alkali is required to initiate expansion in the concrete prism test than in real structures or large concrete blocks produced with the same aggregate and stored in field conditions. For example, the Sudbury aggregate, which is a greywacke-argillite from Ontario, requires an alkali content of at least 5 kg/m$^3$ (8.3 lb/yard$^3$) Na$_2$Oe to produce damaging expansion (i.e. $\geq 0.04\%$) in the concrete prism test and yet the same stone has been implicated in numerous ASR-affected hydraulic and highway structures in Ontario built with concretes at normal cement contents with lower levels of alkali [14,15]. Similarly, the Spratt aggregate from Ontario requires approximately 3 kg/m$^3$ Na$_2$Oe (5 lb/yard$^3$) to produce expansion in the concrete prism test [15], but larger blocks (approximately 0.6 × 0.6 × 2.0 m$^3$, 2 × 2 × 6 ft.$^3$) containing the same aggregate and stored on an outdoor exposure site in Kingston, Ontario expanded and cracked with an alkali content of just 1.9 kg/m$^3$ (3.2 lb/yard$^3$) Na$_2$Oe [26].

The effect of specimen size on threshold alkali content required to initiate expansion with a particular aggregate is illustrated in Fig. 6. The figure shows data for concrete cubes (900-mm, 35.4-in.) stored on an exposure site and both concrete prisms and mortar bars stored over water at 38 °C (100 °F). In all cases, a reactive flint sand comprised 25% of the total mass

Fig. 5. Exposure sites at the University of Texas in Austin (left) and CANMET-MTL in Ottawa (right).

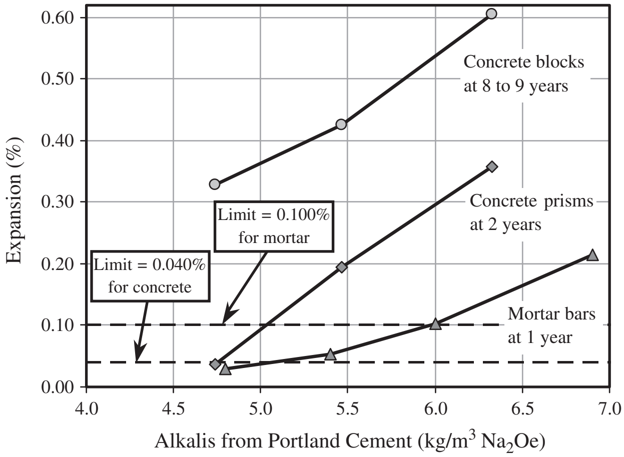

Fig. 6. Relationship between expansion and alkali content for specimens with flint sand in different testing conditions.

of aggregate, the remainder being a non-reactive limestone. Although the prisms and mortar bars were at a younger age compared to the blocks when the final expansion reading was made, both types of specimen had reached ultimate expansion. The expansion of the blocks on the other hand had not ceased. Clearly specimen size has a large impact on expansion and this effect can be largely ascribed to leaching of the alkalis from smaller specimens.

The problem of alkali leaching from specimens stored over water in sealed specimens was first reported by Blanks and Meissner [27]. They detected a build up of alkali ions in the water at the bottom of the containers in which mortar bars ($25\times25\times250$ mm$^3$ gauge length, $1\times1\times10$ in.$^3$ gage length) were stored and explained this based on water condensing on the surface of the bars and running down the bars into the reservoir below, thereby providing transport of the alkalis. The impact of leaching will be less for larger concrete prisms, but is still significant as shown in Fig. 7. This figure shows the build up of alkalis in the reservoir at the bottom of a typical container during the concrete prism test. Three concrete prisms ($75\times75\times300$ mm$^3$, $3\times3\times12$ in.$^3$) containing a reactive siliceous limestone (Spratt) were stored over the water in the container. Assuming a constant reservoir volume of 1.8 l (3.8 pt.) and neglecting any alkalis that may wick up the absorbent material lining the container, it is estimated that approximately 35% of the alkalis originally in the concrete find their way into the water reservoir after 1 year, and as much as 20% after just 90 days. This is very significant especially for aggregates, such as the Sudbury greywacke-argillite discussed above, which react relatively slowly.

The need to boost the alkali content in concrete prisms means that it is not an effective means for determining the threshold alkali level necessary to produce deleterious expansion with a particular aggregate nor is it suitable to evaluate the ASR potential for a specific combination of materials (i.e. a “job mixture”).

When the alkali content of the concrete prism is increased by boosting the portland cement alkalis to 1.25% $Na_2Oe$ (as per CSA and ASTM standard test methods), the test provides a reliable prediction of the field performance of concrete produced with the same aggregate and SCMs, and with high-alkali portland cement (0.90% $Na_2Oe$) as shown in Fig. 8. The expansion data in this figure are from a comprehensive research program at CANMET-MTL in Ottawa [20]. Concrete mixtures were produced with 420 kg/m$^3$ (708 lb/yard$^3$) of cementitious material, six different reactive aggregates, high-alkali cement (0.90% $Na_2Oe$), silica fume and five different fly ashes (2.1% to 91.% CaO and 1.0% to 5.4% $Na_2Oe$). In some mixes, the alkalis were boosted by adding NaOH to the mix in sufficient quantity to bring the alkali level of the portland cement component of the mixture to 1.25% $Na_2Oe$ (as per CSA and ASTM standard test methods), whereas in other mixes no alkalis were added beyond those contributed by the cementing materials. Expansion measurements were made on field-exposed concrete blocks ($400\times400\times700$ mm$^3$, $15.7\times15.7\times27.6$ in.$^3$) and concrete prisms ($75\times75\times300$ mm$^3$, $3\times3\times12$ in.$^3$) stored over water at 38 °C (100 °F).

In the vast majority of cases, the long-term expansion (i.e. up to 10 years) of concrete blocks under field conditions exceeded that of laboratory-stored concrete prisms from the same mixture. This is not surprising as alkali leaching is likely to have little significant impact on the expansion of the larger

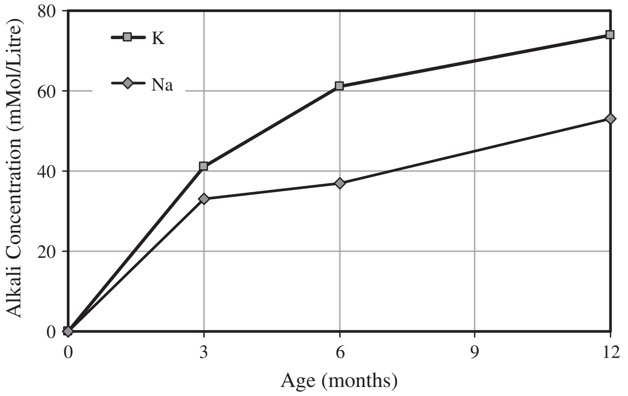

Fig. 7. Concentration of alkalis in water reservoir during the concrete prism test (CSA A23.2-14A and ASTM C 1293).

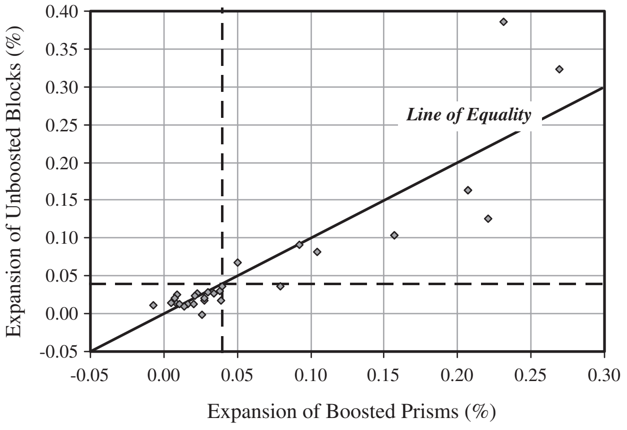

Fig. 8. Comparison of expansion data for blocks stored on exposure site and concrete prisms stored over water at 38 °C.

specimens. For the purposes of this discussion, the performance of the "unboosted" concrete blocks (i.e. without additional alkalis) stored on the exposure site for periods of up to 10 years will be used as the benchmark for evaluating the concrete prism test. These blocks provide the best indication of the likely field performance of the combination of materials used.

Fig. 8 indicates that there is a reasonable correlation between the expansion of prisms with boosted alkalis and the expansion of blocks without additional alkali. More importantly, 19 of the 20 mixes for which data are presented in Fig. 8 give the same result when tested in the concrete prism test (at 2 years) or field-exposure blocks (up to 10 years), i.e. the mix either fails in both tests (expansion $>$ 0.040%) or passes in both tests (expansion $\leq$ 0.040%). The one exception is a mixture containing a crushed greywacke aggregate (from New Brunswick) and 7.5% silica fume; this mix expands by 0.079% at 2 years when tested in the concrete prism test with boosted alkali and by just 0.036% after 10 years when tested in large blocks (without additional alkalis) under field conditions.

The data from this study [20] can be used to estimate (by interpolation) the minimum level of SCM required with a particular reactive aggregate and high-alkali cement to suppress expansion to an acceptable level. Fig. 9 compares the quantity of SCM required to limit the expansion of field-exposed concrete blocks versus laboratory-stored concrete prisms. In most cases, the amounts required are similar in both exposures, but in two cases a significantly greater quantity of fly ash (i.e. $>$5% more) was required in the concrete prism test compared with concrete blocks, suggesting that the prism test with boosted alkalis provides a reasonably conservative estimate of the quantity of SCM required to control ASR expansion.

The results from expansion testing of concrete prisms and blocks can also be compared with field performance in structures. The data from prisms with boosted alkali contents and blocks with no additional alkali indicate that approximately 15% low-calcium (2.4% CaO), low-alkali (1.7% $Na_2Oe$) fly ash is sufficient to control expansion with a reactive greywacke-argillite from Sudbury, Ontario [20]. As discussed earlier, the Lower Notch Dam in Ontario was constructed with a similar aggregate and high-alkali cement (1.08% $Na_2Oe$) with as little as 20% Class F fly ash and is in excellent condition after more than 30 years of service [14].

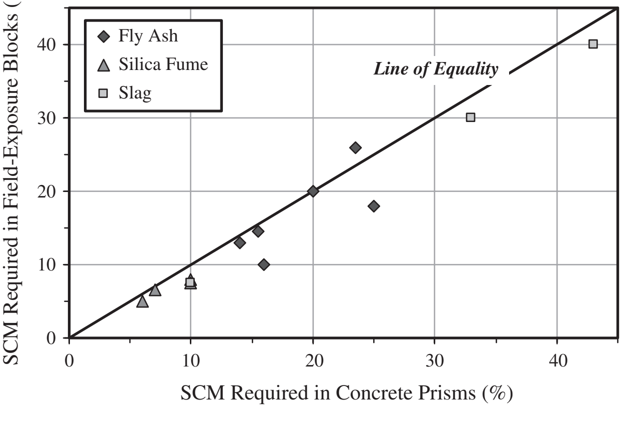

Fig. 9. Level of SCM required to limit expansion ($\leq$0.040%) in laboratory-stored concrete prisms and field-exposed concrete blocks.

Data from concrete prism testing at laboratories around Canada have been used to develop the prescriptive measures specified in CSA A23.2-27A [13] for preventing damaging ASR. Minimum levels of SCM are given in this standard practice and these levels vary depending on the reactivity of the aggregate, the nature of the structure (size, exposure and design life) and the properties of the SCM. When using SCMs to control expansion in accordance with this standard practice the alkali content of the portland cement is limited to a maximum value of 1.00% $Na_2Oe$. Prescriptive limits are not given for high-calcium Type CH fly ash ($>$20% CaO), natural pozzolans, or any fly ash, slag or silica fume with a high level of alkali ($>$4.5% $Na_2Oe$ for fly ash or $\geq$1.0% $Na_2Oe$ for silica fume and slag). However, these materials can be used if they satisfy the performance limits in CSA A23.2-28A [28], which includes controlling expansion in the concrete prism test to less than 0.040% at 2 years.

The main shortcomings of the concrete prism test as a means for evaluating the efficiency of SCMs in controlling damaging ASR are the duration of the test (2 years) and that it cannot be used to determine how the minimum level of SCM changes with the cement alkali content as additional alkalis are required to compensate for leaching effects as discussed earlier.

Concrete prism tests have also been used to evaluate lithium-based compounds for controlling ASR [9,21,29]. Data from these and other tests have confirmed the observations made by McCoy and Caldwell [5] using mortar bars containing Pyrex glass as a reactive aggregate that the amount of lithium required to suppress ASR expansion increases as the quantity of the other alkalis (sodium plus potassium) in the mix increases. Until recently, it was commonly believed that provided the molar ratio of lithium to sodium plus potassium was $[Li]/[Na+K] \geq 0.74$ expansion should be controlled with most reactive aggregates [8]. However, a recent study [9] involving 12 reactive aggregates from Canada indicated that this "standard dose" only worked with half of the aggregates. Three aggregates required 25% to 50% higher doses to control expansion ($<$0.040% at 2 years) whereas expansion could not be controlled with the remaining three aggregates even when the lithium addition was 150% of the "standard dose".

As with SCMs, the current version of the concrete prisms test does not allow the influence of the cement alkalis on the lithium-to-alkali dose to be examined as sufficient alkali has to be added to compensate for the effects of leaching.

The concrete prism test provides valuable and reliable information on the efficacy of SCMs and lithium compounds in controlling expansion when used with high-alkali cement and reactive aggregates; however, further modifications of the test method are required to reduce alkali leaching in this test and, thus, render it suitable for evaluating the impact of cement alkalis.

### 3.4. Accelerated concrete prism test

In 1992, Ranc and Debray [30] proposed accelerating the rate of expansion in the concrete prism test and, hence, shortening its duration by increasing the exposure temperature to 60 °C (140 °F). Since then, there have been a number of studies on the accelerated test, as summarized by Fournier et al. [31], although the test method has yet to be standardized. A recent study indicated that the between-laboratory variability for this test is similar to that for the concrete prism test at 38 °C (100 °F) and that expansion results for concretes stored for 3 months at 60 °C (140 °F) were comparable to results after 12 months at 38 °C (100 °F) as shown in Fig. 10 [30]. In this same study, it was proposed that a three-month expansion limit of 0.040% would be suitable for identifying reactive aggregates.

Touma et al. [32] showed a reasonable correlation between the 3-month expansion of prisms stored at 60 °C (140 °F) and the 12-month expansion of prisms at 38 °C (100 °F) for concretes with and without preventive measures (air-entrainment, SCM and lithium nitrate) as shown in Fig. 11. They proposed that a 6-month expansion limit of 0.04% be used to verify the effectiveness of preventive measures in the accelerated test to be consistent with the use of an extended test duration of 2 years in the standard test at 38 °C (100 °F). However, 2-year data for the standard concrete prism data were not available when the report was published [32] and it is yet unclear whether the accelerated test accurately predicts the outcome of the 2-year standard test.

It has been suggested that the accelerated test be extended to 6 months for evaluating lithium-based admixtures [9] although more data are required to validate the use of this test for this purpose and to determine appropriate performance limits.

Other workers [31] have not been able to reproduce the good correlation between the standard (at 38 °C, 100 °F) and accelerated (at 60 °C, 140 °F) that was reported by Touma et al. [32]. It has been observed that the higher temperature in the accelerated concrete prism test increases the rate of alkali leaching during test, and reduces the pore solution pH due to sulfate ions replacing some of the hydroxyl ions in solution and renders the outcome of the test more sensitive to the selection of the "non-reactive" aggregate for combining with the aggregate under test [31]. These issues need to be resolved before the test achieves wider acceptance.

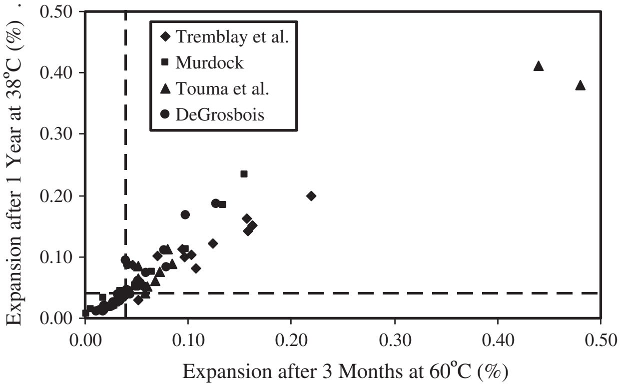

Fig. 10. Comparison of expansions in accelerated vs. standard concrete prism tests for concrete without preventive measures [31].

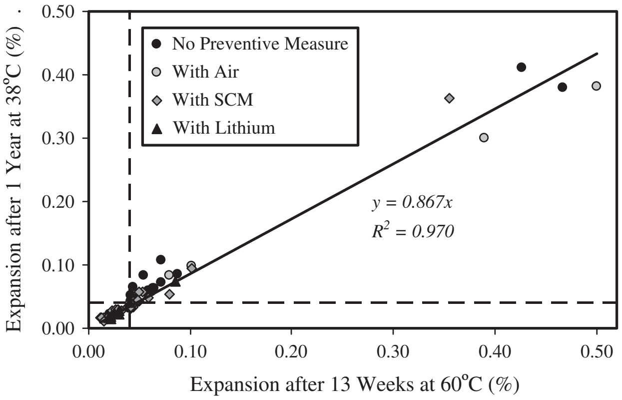

Fig. 11. Comparison of expansions in accelerated vs. standard concrete prism tests for mixtures with and without preventive measures (adapted from Touma et al. [32]).

### 3.5. Mortar bar test (ASTM C 227)

ASTM C 227 *Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations* (*Mortar Bar Method*) was first published in 1950 and is based on the testing methodology described by Stanton in 1940 [1]. The problem of alkali leaching in this test was first reported before the test became standardized [27] and the failure of test to correctly identify the potential reactivity of a numerous rock types is now well established [11,12,15,24,33]. Slowly reactive rocks such as certain gneisses, greywackes, argillites, quartzites and meta-volcanics may not expand in this test when combined with high-alkali cement [34,35].

This test is not suitable for determining the threshold level of alkali required to initiate expansion with a particular aggregate. Fig. 6 shows that the alkali content required to produce expansion in this test is much greater than that required in the concrete prism test or field-exposed concrete blocks. As a result of the many shortcomings of this test, it is not recommended for use as a method either for identifying the reactivity of an aggregate or for determining the level of prevention required to suppress expansion.

### 3.6. Pyrex mortar bar test (ASTM C 441)

The Pyrex mortar bar test (ASTM C 441) was first approved by ASTM in 1959. The test was originally developed by researchers at the U.S. Bureau of Reclamation for the specific purpose of evaluating "siliceous admixtures" (i.e. pozzolans) for use in the construction of the Davis Dam to address concerns of ASR [36]. The test is essentially the same as ASTM C 227 except that Pyrex (borosilicate) glass is used as the reactive aggregate. ASTM C 441 (or ASTM C 227 with borosilicate glass) is referenced in a number of ASTM material specifications as shown in Table 1.

This test method has been criticized for a variety of reasons including the following:

- Variability between sources of Pyrex glass may cause different mortar bar expansions [37,38]

Table 1
Limits used for ASTM C 441 (Pyrex mortar bar test) in various material specifications

| Specification | Limit |
|---|---|
| ASTM C 618 Fly Ash and Natural Pozzolans | 14-day expansion of cement/fly ash blend ≤ expansion of control mix with low-alkali cement (≤ 0.60% $Na_2Oe$) |
| ASTM C 989 Ground granulated blast-furnace slag | If job cement and proportions of cement and slag are known: 14-day expansion ≤ 0.020%. Otherwise: 14-day expansion of cement/slag blend ≤ 25% of the expansion of control mix with the high-alkali cement only (i.e. slag should reduce expansion by at least 75% compared with the control) |
| ASTM C 1240 Silica Fume | 14-day expansion of blend of 90% cement and 10% silica fume ≤ 20% of the expansion of control mix with the high-alkali cement only (i.e. 10% silica fume should reduce expansion by at least 80% compared with the control) |
| ASTM C 595 Blended Hydraulic Cement | 14-day expansion of blended cement ≤ 0.020% and 56-day expansion of blended cement ≤ 0.060% |
| ASTM C 1157 Hydraulic Cement (Option R) | 14-day expansion of hydraulic cement ≤ 0.020% and 56-day expansion of hydraulic cement ≤ 0.060% |

- Differences in the particle shape of crushed Pyrex results in differences in water demand (mortar flow) and, thus, different w/cm values, which may impact the expansion [39]
- Pyrex contains appreciable quantities of alkali (typically around 4% $Na_2Oe$) which may be released during test thus interfering with the action of the pozzolan [40,41]
- Pyrex glass may react more rapidly than the pozzolan or slag being tested, thus masking their beneficial effects [33]
- The performance limits are too severe overestimating the amount of pozzolan or slag that is required to control damaging expansion [42,43]
- The amount of pozzolan or slag required to control expansion is influenced by, among other factors, the nature of the reactive aggregate and this is not taken account of in tests with a standard reactive aggregate such as Pyrex [42]. This issue may be of greater concern for evaluating lithium compounds as recent data indicate that the effectiveness of lithium in terms of controlling ASR varies widely with aggregate type [9].

Despite the shortcomings of this test method it is still referenced by a number of specifications or guide specifications in the United States including:

- ASTM C 33 Standard Specification for Concrete Aggregates
- AASHTO Guide Specification for Highway Construction [44]
- PCA Guide Specification for ASR [45]

To the authors' knowledge, ASTM C 441 is not used in any national specifications outside of the U.S.A.

There have been various suggestions put forward to address some of the concerns regarding ASTM C 441 including using a different standard reactive aggregate that is more consistent and contains less alkali such as Vycor glass [40] or fused silica and changing the performance limits. An expansion limit of 0.10% at 56 days has been proposed by a number of workers [42,43,46] as the expansion of the mortar bars tends to reach a plateau at this age, as opposed to the rapid expansion occurring at 14 days, and the additional time allows slowly reacting pozzolans and slag to make more of an impact. However, even using this criterion, Lane [43] showed that 35 to 40% of low-calcium fly ash (5 sources with less than 6% CaO) or 50% slag was required to control expansion with Pyrex and high-alkali cement (0.92% $Na_2Oe$), whereas only 15% fly ash and 35% slag was required to control expansion in concrete with a natural reactive aggregate and cement alkalis raised to 1.25% $Na_2Oe$ [Note: the concrete prism test used a cementitious materials content of 377 kg/m$^3$ (636 lb/yard$^3$) as opposed to a content of 420 kg/m$^3$ (708 lb/yard$^3$) specified in ASTM C 1293 and CSA A23.2-14A]. Even control mixes with a low-alkali cement of 0.60% $Na_2Oe$ failed the 56-day limit of 0.10% (in fact the expansion was greater than 0.20%) and an alkali level of 0.50% $Na_2Oe$ was required to meet the limit. The performance limits in ASTM C 595 and C 1157 (0.020% at 14 days and 0.060% at 56 days) were only met by control mortar bars produced with a cement with an alkali content of 0.40% $Na_2Oe$.

Regardless of whether the problems associated with the variability, high reactivity and alkali content of Pyrex glass can be overcome, the main problem with this test (or any test using a standard reactive aggregate) remains that it cannot account for the influence of aggregate type; i.e. different aggregates require different levels of prevention. As such, tests using standard reactive aggregates can only provide a comparative measure of the performance of different cements, pozzolans and slag for controlling ASR.

### *3.7. Accelerated mortar bar test (ASTM C 1260, ASTM C 1567 and CSA A23.2-25A)*

The accelerated mortar bar test (AMBT) was developed by Oberholster and Davies [47,48] at the National Building Research Institute (NBRI) in the Republic of South Africa about 20 years ago. The test involves the immersion of mortar bars in 1M NaOH solution at 80 °C (176 °F) for 14 days and produces results within 16 days. The test was originally developed for identifying reactive aggregates and was adopted for this purpose in 1994 by both ASTM (as C 1260 – formerly P 214) and CSA (as A23.2-25A). Although the test is now widely used in North America, it is generally considered overly severe as it identifies many aggregates as reactive despite good performance in the field and in concrete prism expansion tests. Consequently, the test should only be used to accept and not reject aggregates. Furthermore, if an aggregate fails the test, the concrete prism test should be used to confirm the results before an aggregate is either rejected or conditions are put on its use [49].

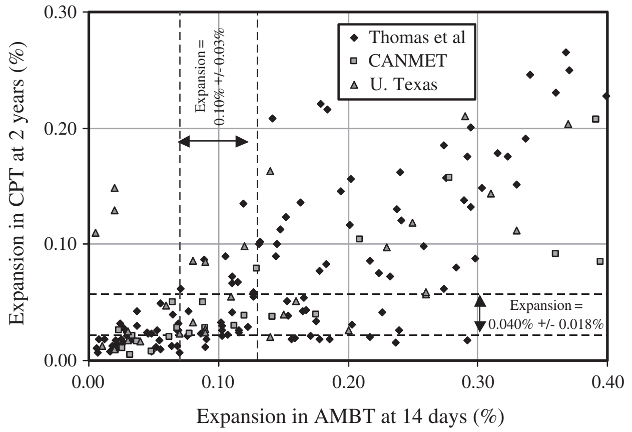

Fig. 12. Comparison between expansion at 2 years in CPT and expansion at 14 days in AMBT.

Soon after development of the AMBT, it was proposed that it might also be a useful tool for evaluating the efficiency of pozzolans and slag for controlling expansion [48,50–53]. Initially, there was a reluctance to adopt this method of evaluation due to the lack of a clear explanation of why it works. It is generally accepted that the principal mechanism by which pozzolanic materials suppress ASR is by reducing the quantity of alkali hydroxides in the pore solution. The accelerated mortar bar test method would seem to offset this primary function by providing the system with an ‘inexhaustible’ supply of NaOH. Recently, however, it has been demonstrated that mineral admixtures may still be effective in suppressing the pore solution alkalinity during a 14-day immersion period and that this is the reason why they are still able to suppress expansion despite the abundant availability of alkalis [51–53].

It should be recognized that the mechanisms by which SCMs control the concentration of alkali hydroxides (and thus the expansion) in concrete and the AMBT are somewhat different. In concrete, the source of alkalis is internal and SCMs deplete the alkalis in solution by dilution (i.e. less portland cement) and by binding sodium and potassium in the hydration products; provided sufficient SCM is used, the effect is permanent. In the AMBT, the predominant source of alkalis is external and SCMs work by both retarding the rate of ingress of alkalis in to the mortar bar and by binding a portion of the alkalis in solution. However, the effect is only temporary as, eventually, sufficient alkalis will penetrate into the bar and cause damaging expansion. Thus, any correlation that exists between the results of the two tests is fortuitous.

The AMBT can be used to evaluate preventive measures using CSA Standard Practice A23.2-28A in Canada. A modified version of ASTM C 1260 for evaluating pozzolans and slag was published as ASTM C 1567 in 2004, but modifications of the test were used for this purpose by many agencies in the U.S.A. for a number of years prior to its adoption by ASTM.

Thomas and Innis [53] published data for 70 different combinations of SCM and aggregates tested in both the CPT and AMBT, and demonstrated that there was a reasonable correlation between the 2-year expansion in the former and the 14-day expansion in the latter. Although there was no single relationship, they concluded that combinations of materials that expanded less than 0.10% at 14 days in the AMBT had a low risk of failing the 0.040% limit at 2 years in the CPT [53]. However, the same data showed that many combinations failed the mortar bar limit (i.e. expansion > 0.10% at 14 days) but performed satisfactorily in concrete (i.e. expansion < 0.04% at 2 years).

The data from Thomas and Innis [53] are reproduced in Fig. 12 with additional data from studies at the University of Toronto, CANMET-MTL in Ottawa and the University of Texas at Austin. The figure shows data from 184 different combinations of SCM and aggregates tested in both concrete and mortar. Also shown in the figure are zones representing the expansion limits for each test plus or minus 1.96 times the estimated standard deviation (based on the precision statements in the ASTM standard test methods). For the AMBT, this zone represents expansions between 0.100% ± 0.030% and for the CPT the range is 0.040% ± 0.018%. The outcome of the test for any data points that fall within these “grey zones” may be considered to be inconclusive. Using this approach, the outcome of the tests for the 184 combinations of materials shown in Fig. 12 are summarized in Table 2.

In 73 out of 184 (40%) cases, the outcome of either or both test is inconclusive; in other words, the measured expansion is too close to the limit to determine with confidence that the combination either passed or failed. In 99 out of 184 (54%) cases, the outcome is the same for both tests. In only 12 of 184 (6.5%) cases, there is a significant disagreement between the outcome of the two tests. Perhaps of most concern are the cases where a combination of materials passes the accelerated test (expansion < 0.070% at 14 days) but fails the concrete prism test (expansion > 0.052% at 2 years). However, this only occurred in 3 (1.6%) cases out of the 184 material combinations tested. All three cases are for mixes without SCM (i.e. control mixes) and the expansion in the mortar test remained low even when the test duration was extended to 28 days. The mineralogy of these aggregates is currently under investigation.

The data from these studies were also used to determine the minimum level of a particular SCM required to control expansion with a given aggregate to less than 0.10% at 14 days in the AMBT and less than 0.04% at 2 years in the CPT. The minimum level was only determined in cases where an SCM had been tested with the aggregate at 2 or more different

Table 2
Comparison of test results from the concrete prism test and accelerated mortar bar test for 184 combinations of materials

| Concrete prism test | Accelerated mortar bar test | Frequency of outcome |
|---|---|---|
| Pass (<0.012% at 2 years) | Pass (<0.070% at 14 days) | 33 (18%) |
| Fail (>0.052% at 2 years) | Fail (>0.130% at 14 days) | 66 (36%) |
| Pass (<0.012% at 2 years) | Fail (>0.130% at 14 days) | 9 (4.9%) |
| Fail (>0.052% at 2 years) | Pass (<0.070% at 14 days) | 3 (1.6%) |
| Inconclusive (CPT = 0.012% to 0.052%, AMBT = 0.070% to 0.130%, or both) | | 73 (40%) |
| Total | | 184 |

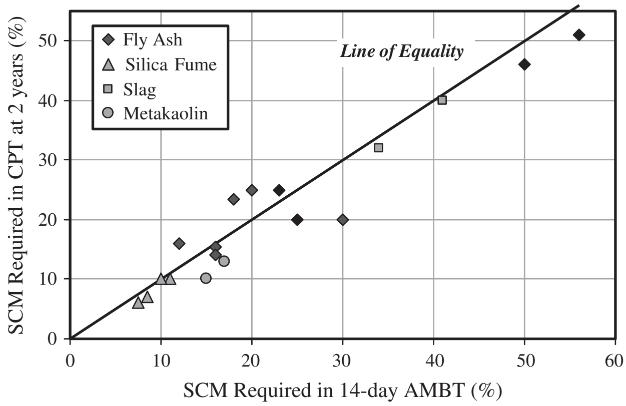

Fig. 13. Comparison between the minimum level of SCM required to control expansion in the CPT and AMBT.

replacement levels. In most cases, the minimum level was determined by interpolating between a mix that failed the limit and one at a higher replacement level that passed the limit. In a few cases, the minimum level was determined by extrapolation as the mixes failed at all levels of replacement tested. Fig. 13 shows that the minimum SCM level determined by the two different test methods is in close agreement.

In summary, the data indicate that the modified version of the AMBT (ASTM C 1567) can be used with a reasonable level of confidence to determine whether a combination of reactive aggregate and SCM is likely to result in deleterious expansion when used in concrete with a high-alkali cement or what level of SCM is required to suppress expansion when a reactive aggregate is used in concrete with high-alkali cement. This is somewhat surprising considering that the action of the SCM is somewhat different in the two test methods (i.e. SCM works by binding alkali in the CPT and by both binding alkali and retarding the diffusion of alkali into the test specimen in the AMBT). It is not possible to use the AMBT in its current form to explore how the minimum level of SCM is influenced by the amount of alkali contributed by the portland cement – i.e. to determine whether reduced SCM levels can be used with lower alkali cements.

A more detailed discussion on the use of the AMBT to evaluate SCMs as preventive measures for ASR, including alternative performance limits and correlation with field performance is presented elsewhere by the authors [54].

It has been proposed that the AMBT may be modified to determine the threshold cement alkali level required to initiate deleterious expansion with a particular aggregate [55]. Stark and coworkers adjusted the alkali concentration of the soak solution in the test to represent the expected alkali concentration in the pore solution of the mortar bar using the following equation developed by Helmuth [56]:

$$[\mathrm{OH}^-] = 0.339(\mathrm{Na_2Oe})/(W/C) + 0.022 \pm 0.06\ \mathrm{mol/l} \qquad (1)$$

where:

$[\mathrm{OH}^-]$ hydroxyl ion concentration in the pore solution
$\mathrm{Na_2Oe}$ equivalent alkali content of the cement
$W/C$ water-to-cement ratio

Table 3
Proposed expansion limits (at 14 days) for modified accelerated mortar bar test when determining threshold level of cement alkali

| Alkalis in soak solution (mol/l NaOH) | Expansion limit at 14 days (%) |
|---|---|
| ≤0.60 | 0.02 |
| 0.60 to 1.00 | 0.02 to 0.08 (varying linearly with OH) |
| ≥1.00 | 0.08 |

Table 3 shows the 14-day expansion limits proposed by Stark and coworkers [55]. These expansion limits were set based on matching the field performance of a reactive quarried granite-gneiss from Delaware which tends to give low expansion in the standard AMBT despite poor performance in the field. There are little other data to support the selection of expansion limits.

Touma and coworkers [32,57] reported data for four aggregates tested using the modified procedure proposed by Stark et al. [55] and the accelerated CPT (i.e. 3 months at 60 °C, 140 °F) using cements of varying alkali content and found a reasonable agreement between the outcome of the two tests.

Shehata and Thomas (unpublished) compared the expansion of three different aggregates in the CPT (i.e. 2 years at 38 °C, 100 °F) with cements of different alkali contents with the expansion of the same aggregate in the AMBT with the soak solution hydroxyl ion concentration adjusted on the basis of the following equation based on the review of pore solution data from Nixon and Page [58]:

$$[\mathrm{OH}^-] = 0.7\mathrm{x}(\mathrm{Na_2Oe})\mathrm{mol/l} \qquad (2)$$

where:

$[\mathrm{OH}^-]$ hydroxyl ion concentration in the pore solution
$\mathrm{Na_2Oe}$ equivalent alkali content of the cement

The results are shown in Figs. 14, 15, and 16 for reactive aggregates Sudbury (greywacke–argillite), Spratt (siliceous limestone) and Jobe (chert) sand, respectively. For Sudbury and Spratt, there is a good agreement between the threshold alkali level required to initiate expansion as determined by the two tests. For Jobe sand, the magnitude of expansion is higher and the threshold alkali level lower when the aggregate is tested

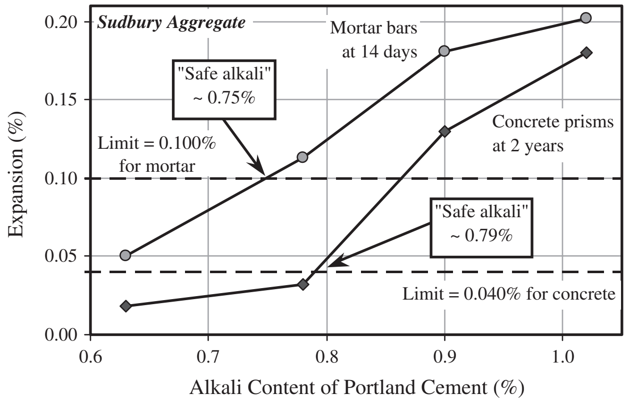

Fig. 14. Effect of cement alkalis on expansion in CPT and AMBT with modified soak solution – Sudbury aggregate.

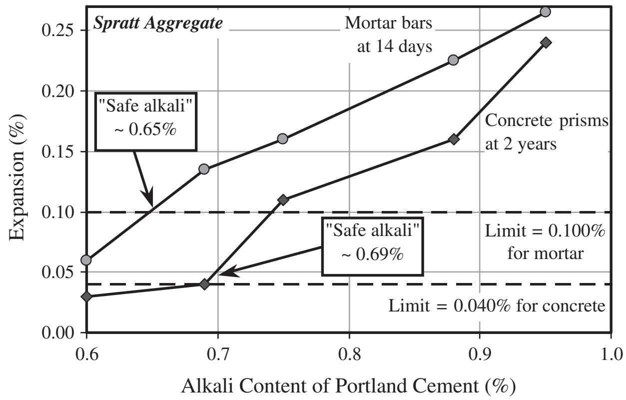

Fig. 15. Effect of cement alkalis on expansion in CPT and AMBT with modified soak solution – Spratt aggregate.

in the modified AMBT compared with the CPT. Note that only 1-year CPT data are available for Jobe sand. Two-year data will result in an increase in the magnitude of expansion and possibly a reduction in the threshold alkali level required to produce an expansion greater than 0.040%. However, it is unlikely that there will be sufficient change in the expansion between 1 and 2 years to account for the differences observed between the data for the AMBT and CPT shown in Fig. 16.

Although a good agreement is obtained between the alkali threshold determined by modifications to the AMBT and that determined by the CPT, it should be remembered that the CPT is not a good indicator of the threshold alkali level as additional alkali is needed in this test to produce damaging expansion (see Fig. 6 and earlier discussion). Further modifications to the AMBT to make it suitable for determining the threshold alkali level for different aggregates should be made by comparing the outcome to appropriate benchmark tests. This would involve the long-term testing of large blocks under field conditions using concretes produced with a range of reactive aggregates and varying cement alkali levels. Ideally mixtures should be cast with and without SCM to determine the interaction between cement alkalis, pozzolans and slag.

In its current form, the AMBT is not suitable for evaluating lithium-based compounds. Expansion testing of concrete and mortars stored in conditions of high humidity (e.g. ASTM C 1293 and C 227) has demonstrated that the amount of lithium required to suppress expansion is a function of the quantity of other alkalis (i.e. Na+K) in the system and of the level of reactivity of the aggregate [8,9]. The AMBT swamps the system with an inexhaustible supply of alkalis (i.e. NaOH) making it impossible for the lithium in the mortar bar to control damaging ASR. Stark et al. [55] demonstrated that lithium could control expansion in the accelerated mortar bar test provided a sufficient amount was added to the soak solution. Their data showed that lithium would suppress expansion provided the [Li]/[Na] molar ratio of the soak solution was in the region of 0.67 to 1.00, which is similar to the doses generally recommended for concrete [8].

Fig. 17 shows expansion data (Thomas, unpublished) for mortars with a reactive rhyollite from New Mexico, high-alkali cement plus lithium at various doses, tested in ASTM C 227 and “modified” ASTM C 1260 (AMBT). For mortar bars stored over water at 38 °C (100 °F) (ASTM C 227 conditions), expansion was suppressed when sufficient lithium was added to the mortar to achieve a lithium-to-alkali molar ratio of [Li]/[Na+K]=0.56 (75% of the recommended dose of 0.74). For mortar bars stored in 1 M NaOH at 80 °C (176 °F) expansion occurred even when the lithium concentration in the bar was [Li]/[Na+K]=0.74. When lithium was added to the soak solution to achieve the same lithium-to-alkali ratio in solution as that used in batching the mortar, a good agreement was seen between the results of the modified test and ASTM C 227.

It has been observed in a number of studies that a significant proportion (up to 50%) of the lithium added to cement pastes, mortars or concretes is bound by the hydrates and not available to the pore solution [59–62]. Consequently, it may be appropriate to user lower doses of lithium in the soak solution of the AMBT to better represent the composition of the pore solution in the mortar bar. Further testing is in progress at the authors' laboratories and elsewhere [59] to determine appropriate modifications to the AMBT to render it suitable for evaluating lithium-based compounds.

### 3.8. Other test methods

A number of other tests have been used to evaluate SCMs as a means for controlling damaging ASR in concrete. In addition to using the Pyrex mortar bar to evaluate pozzolans for the Davis Dam, the specification included a “Reduction-in-Alkalinity Test” [36], which was a modification of the “Quick Chemical Method” for evaluating aggregates (ASTM C 289 first published in 1952). The test involved immersing the pozzolan in sodium hydroxide solution at elevated temperature (80 °C, 176 °F) for 24 h and measuring the reduction in alkalinity and the quantity of silica dissolved [36]. A later version of this test incorporated a quantity of calcium hydroxide in addition to the pozzolan and sodium hydroxide solution [63] and eventually the test was further modified by omitting the sodium hydroxide and measuring the alkalis that are “available” in a lime-pozzolan mix after 28 days storage at 38 °C (100 °F) –

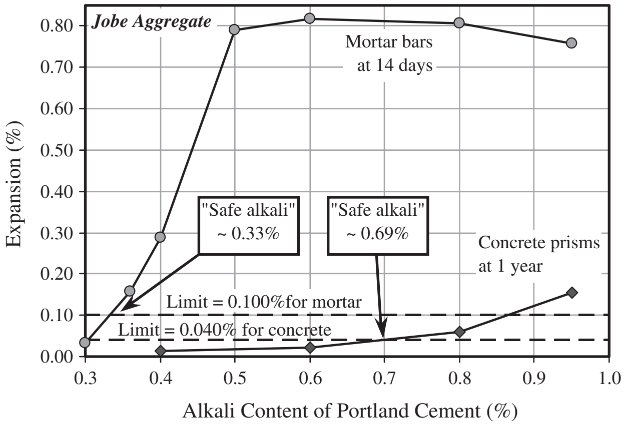

Fig. 16. Effect of cement alkalis on expansion in CPT and AMBT with modified soak solution – Jobe aggregate.

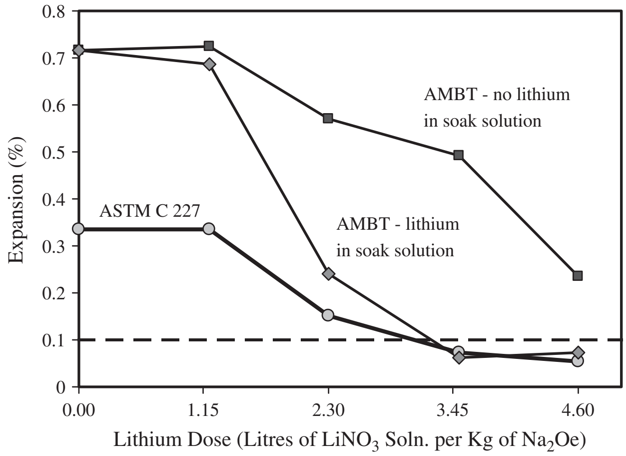

Fig. 17. Comparison of expansion in ASTM C 227 with expansion in AMBT modified with lithium in the soak solution – rhyollite from New Mexico.

this is the "Available Alkali Test" in ASTM C 311. This test was recently dropped as an optional requirement for pozzolans in ASTM C 618 as it was generally considered that the data from this test did not relate well to the performance of the pozzolan with regards to ASR.

Autoclave mortar bar tests have been used to determine the effectiveness of SCMs [64,65]. In the test proposed by Duchesne and Bérubé [65] mortar bars are stored in a moist cabinet for 2 days and then placed in a autoclave at 130 °C (266 °F) and 0.17 MPa (25 psi) for 5 h. The results of the tests for SCMs were found to be in reasonable agreement to results for the same SCM-aggregate combination tested in the CPT except that the autoclave test tends to give conservative results (i.e. requires more SCM) compared to the CPT and may be too severe for certain fly ashes [65]. The test requires the alkali content to be raised to 3.5% $Na_2Oe$ by mass of cement and this renders the test unsuitable for exploring the influence of cement alkalis.

The Chinese Accelerated Mortar Bar Test (CAMBT) or Concrete Microbar Test has attracted interest recently [66,67] as it offers the advantage of using larger aggregate sizes (mortar bar has a $40 \times 40$ mm$^2$ cross-section) and possibly a shorter duration (7 days). The test may also be suitable for alkali–carbonate reactive rocks [66]. However, little data are available for SCMs in this test and further research is required.

## 4. Concluding remarks

The ideal test method should be capable of rapidly evaluating the potential for ASR expansion for a particular combination of materials (i.e. job mixture). In other words, the test should have the following attributes:

- The test should be reliable in terms of predicting how the combination of materials will behave under field conditions.
- The test should use the reactive aggregate (or the combination of aggregates) under consideration rather than a standard reactive aggregate (such as Pyrex glass).
- The test should not involve excessive processing of the aggregate (such as crushing a coarse aggregate to allow it to be tested in mortar).
- The test should be capable of evaluating the contribution of the cement alkalis rather than requiring an increase in the level of alkali.
- The test should be rapid, providing results in weeks or months rather than years.
- The test should be capable of assessing all types of SCM, lithium compounds and combinations of SCM and lithium (with cements of different alkali level).

Table 4 presents a summary of the tests discussed in this paper and indicates which of the above attributes can be conferred on the tests.

None of the tests currently used for evaluating preventive measures for ASR meets all of the criteria. In terms of reliability, the concrete prism test offers the best prediction of field performance when SCMs or lithium compounds are used with high-alkali cement and reactive aggregates. Its main shortcoming is the length of time required to run the test. Accelerating the test by raising the temperature to 60 °C (140 °F) appears to be promising, but there are a few issues that need to be resolved. The accelerated mortar bar test (AMBT) has as its main advantage a relatively short duration, but the price for speed seems to be a loss in reliability. However, it is possible to use the AMBT to determine the minimum amount of SCM required to suppress expansion with a particular aggregate when that aggregate is used with high-alkali cement. The risk of damaging expansion occurring in the field is considered to be low when using a combination of materials that passes the performance criteria for the AMBT.

Table 4
Comparison of different test methods and criteria for the "ideal test"

| Test | Reliable | Job aggregate | Unprocessed aggregate | Job cement | All SCMs | Lithium compound | Rapid |
|---|---|---|---|---|---|---|---|
| Ideal test | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Field performance | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Concrete prism (C 1293) | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ | ✗ |
| Accelerated prism | ? | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ |
| Accelerated mortar bar (C 1260) | ? | ✓ | ✗ | ✗ | ✗ | ✗ | ✓ |
| Mortar bar (C 227) | ✗ | ✓ | ✗ | ✗ | ? | ? | ? |
| Pyrex mortar bar (C 441) | ✗ | ✗ | ✗ | ? | ✓ | ✓ | ✓ |

A disappointing feature of the CPT and AMBT is that the tests cannot be used in their current form to determine the influence of cement alkalinity (or to evaluate "job mixtures"). Using low-alkali cement to control the alkali content of the concrete below the threshold for expansion or using it in combination with SCMs are viable approaches for controlling ASR, but the safe levels of alkali or safe combinations of low-alkali cement and SCM cannot be determined by existing laboratory tests.

The following list provides some suggestions for modifying the tests to improve their reliability and extend their application:

*Concrete Prism Test.* Leaching of alkalis during testing must be minimized or, preferably, eliminated. This may be achieved by changing the conditions of the test such that moisture can enter the system as required, but without there being direct contact between a large reservoir of water (or condensate) and the surface of the specimen. Using large specimens will also reduce the impact of leaching however, storage and regular manipulation of such specimens for length change measurements would possibly become an issue.

*Accelerated Concrete Prism Test.* As with the standard CPT, leaching of alkalis must be addressed. A method needs to be developed for identifying aggregates that are suitable for use as "non-reactive" aggregates to be combined with the aggregate under test. The implications of sulfate ions replacing some of the hydroxyl ions in the pore solution (i.e. lowering the pH) need to be quantified and, if necessary, the phenomenon needs to be mitigated.

*Accelerated Mortar Bar Test.* The use of modified soak solutions to account for cement alkalinity in systems either with or without pozzolans warrants further exploration. It may be possible to determine the appropriate composition of the soak solution from the chemical composition of the cementing system (i. e. portland cement plus SCMs) using an approach similar to the "model" developed by Thomas and Shehata [68].Further work is required to determine the appropriate soak solution composition when evaluating lithium-based compounds using this test.

Ongoing research at the authors' laboratories and elsewhere is directed towards improving these test methods and developing alternative tests. However, it is essential that test methods and associated test limits be developed with consideration to appropriate benchmarks. The evidence presented here clearly indicates that the only suitable benchmarking is derived from field performance of structures or large blocks placed on exposure sites. It is inappropriate to evaluate a test method or test limit using other laboratory tests that do not themselves have an excellent correlation with field performance. The authors of this paper have developed exposure sites in Canada, the U.K. and U.S.A., and are continuing to extend the range of concrete mixtures under study. There is a clearly need to develop an extensive study with a range of aggregates produced with concretes of varying alkali level with and without other preventive measures.

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