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# Evaluation of accelerated test methods for determining alkali-silica reactivity of concrete aggregates

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## Abstract

For assessing the applicability of a newly proposed Chinese accelerated mortar bar test (CAMBT) to overseas aggregates and determining the appropriate aggregate size fraction for the test, the influence of aggregate particle size on ASR expansion was studied at 0.15–0.80 mm, 1.25–2.50 mm and 2.5–5.0 mm size fractions on nine aggregates from a range of sources. Correlation between expansions in the CAMBT and in the accelerated mortar bar test (AMBT), and correlations between the two accelerated tests and the Concrete Prism Test (CPT) were examined. The results indicate that, for most aggregates tested, 0.15–0.80 mm is not the most sensitive aggregate size to expansion in the CAMBT, especially at early period before 10 days. The 1.25–2.50 mm size fraction of all the nine aggregates, gives the highest early expansion (first 10 days). Correlation between expansions in the CAMBT and expansions in the AMBT is satisfactory. However, the correlations in expansions of both AMBT and CAMBT with the CPT are very poor. A better correlation between expansions in the modified CAMBT and in the CPT is obtained when 2.5–5.0 mm aggregate particles was used, but further tests are necessary to establish the full reliability of the test.

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*Keywords:* Alkali-silica reaction; Alkali-carbonate reaction; Accelerated testing method

## 1. Introduction

A tremendous amount of work has been done over the past few decades to develop quick and reliable test procedures for determining the potential alkali-reactivity of concrete aggregates. The accelerated mortar bar test (AMBT) (e.g. ASTM C1260, CSA A23. 2-25A, RILEM TC191-ARP-02) that was originally proposed by Oberholster and Davis in 1986 is probably the most widely used accelerated method for testing the potential alkali-silica reactivity of concrete aggregate [1–4]. The concrete Prism Test (CPT) (e.g. CSA A23.2-14A, ASTM C1293, RILEM TC191-ARP-03) is recognized as the most reliable test procedure and has been used for the evaluation of both alkali-silica and alkali-carbonate reactivity as well as the potential for reactivity in mixtures containing SCMs [5–7]. However, these accelerated laboratory test procedures still have their limitations. For some aggregates, there was a relatively poor correlation between expansions measured in the AMBT and the CPT [8–11]. The disagreements include that the AMBT failed to recognize the non-reactive character (based on field performance records) of some aggregates, while failing to identify some other aggregates that were reactive in the CPT. The at least one-year testing period for alkali reactivity and two years for mixtures containing SCMs required by the CPT is too long in most cases, which limits its use as a quality control test in engineering practices. The CPT is often used as a benchmark for assessing accelerated tests.

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The Chinese autoclave method proposed by Tang et al. in 1983 [12] has been used in China and has shown some satisfactory records in identifying the potential reactivity of aggregates outside China [13]. However, the very small amount of aggregate sample and the small size of the testing specimens used in the method make it more suitable for use as a research tool rather than as a quality control test for rock quarries. Some researchers also have doubts that other causes of expansion may contribute to the expansion in the test at 150 °C.

In order to determine the potential alkali-silica reactivity of aggregate more quickly and accurately to comply with the fast growing infrastructure construction in China, a new test method (Chinese accelerated mortar bar method—CAMBT) was developed recently in China by combining the advantages of the Chinese autoclave method and the AMBT method [14]. The main parameters in the new method, the AMBT and the autoclave method are compared in Table 1.

In the CAMBT, a single size fraction of fine aggregate (0.15–0.80 mm) and a high-alkali system of 1.5% $Na_2Oeq$ (obtained through the addition of KOH to a low-alkali cement) are used, which are the same as in the Chinese autoclave test. Three series of tests were performed with cement-to-aggregate ratios of 10:1, 2:1 and 1:1. The water-to-cement ratio was fixed at 0.33. The mortar bar size was 40 × 40 × 160 mm. The storage conditions and testing procedures are similar to the AMBT method, except that the initial length measurement (or zero reading) is made after 4 h of immersion in 1 M NaOH at 80 °C. The method was developed using typical Chinese aggregates and allows determining the alkali-silica reactivity of aggregates within 7 days.

The common approaches to accelerate the reaction/expansion process in these accelerated procedures are using large proportion of fine aggregate particles and high temperature, high-alkali regime, but with significant difference in the mix compositions, such as specimen size, aggregate gradation etc. (Table 1). The five graded aggregate fractions used in the AMBT are derived from ASTM C227, the standard mortar bar test, while the 0.15–0.80 mm aggregate fraction used in the CAMBT follows the Chinese autoclave method. Previous study showed that, for 25 × 25 × 285 mm mortar bars cured at 38 °C and high humidity environment, there exists a pessimum particle size that could induce largest mortar expansion [15]. However, little work has been reported on the effect of particle size on 40 × 40 × 160 mm mortar bar expansion in 1 M NaOH solution at 80 °C.

In terms of chemical reaction, reducing the particle size can increase the specific surface area of the reactant thus inducing a higher reaction degree. However, expansion due to AAR is a transformation process from chemical energy into mechanical action. The expansion does not necessarily increase proportionally with the degree of reaction or the amount of reaction products being produced. Some aggregates (for example, some greywackes) may effectively exhibit significant expansion without much reaction product being produced. Researchers have confirmed that the microstructural and textural characteristics of rocks in an aggregate played an important role in the alkali-silica reaction and expansion processes [16,17]. Also, in the case of the alkali-carbonate reaction (ACR), only aggregates with a specific texture (i.e. dolomitic limestones with discrete dolomite rhombs, 10–50 μm in size, disseminated in a fine-grained matrix of calcite and clay minerals) shows large expansion, and measured expansions of laboratory test specimens do not necessarily increase with increasing dolomite crystal content in the aggregate or with the noticeable extent of dedolomitization observed in the laboratory test conditions.

The usefulness of these accelerated tests depends on their reasonable correlation with the CPT result. For assessing the applicability of the CAMBT to overseas aggregates and determining the appropriate aggregate size fraction for the test, the effect of aggregate particle size on ASR expansion was studied on nine aggregates from a range of sources. Correlations between expansion in the new test and in the AMBT and the CPT were examined.

Table 1
Parameters in accelerated tests for alkali-silica reactivity

| Parameters | AMBT | Autoclave method | CAMBT |
|---|---|---|---|
| Water-to-cement ratio | 0.47 | 0.30 | 0.33 |
| Cement alkalis ($Na_2Oeq.$) | 1.0 ± 0.1%[a] | 1.5%[b] | 1.5%[b] |
| Aggregate size (mm) | 0.15–5.0[c] | 0.15–0.80 | 0.15–0.80 |
| Bar size (mm) | 25 × 25 × 285 | 10 × 10 × 40 | 40 × 40 × 160 |
| Cement-aggregate ratio | 1:2.25 | 10:1, 5:1, 2:1 | 10:1, 2:1, 1:1 |
| Curing temperature | 80 °C | 150 °C | 80 °C |
| Storage solution | 1.0 M NaOH | 10% KOH | 1.0 M NaOH |
| Zero length | 24 h in water @ 80 °C | 24 h moist @ 23 °C | 4 h in 1 M NaOH @ 80 °C |
| Criteria | 0.10% @ 14 days | 0.10% @ 6 h | 0.10% @ 7 days |

[a] Use high-alkali cement.

[b] Use low-alkali cement, add KOH to mix water.

[c] Five required size fractions.

## 2. Materials and methods

### 2.1. Aggregates

Eleven aggregates, from Canada, USA, Norway and Australia were used (Table 2). The aggregates represent a variety of rock types of sedimentary, igneous and metamorphic origins, for which AMBT and CPT expansion results are available.

The aggregates were crushed and sieved to the following three size ranges: 0.18–0.80 mm, 1.25–2.50 mm and 2.50–5.0 mm.

### 2.2. Cement and cement-to-aggregate ratio

In the proposed new test procedure, a low-alkali cement was to be used, with the cement alkali content adjusted to 1.5% $Na_2Oeq$ by adding KOH to the mixing water. A low-alkali cement (0.58% $Na_2Oeq$) was first tried at the CANMET laboratory, but the paste was very harsh at the water-to-cement ratio of 0.33 when adding KOH. Therefore, a CSA type 10 (ASTM Type I) high-alkali cement with 0.91% $Na_2Oeq$ was used without the addition of KOH in this study.

A series of preliminary tests were performed using three cement-to-aggregate ratios (e.g. 10:1, 2:1 and 1:1) to identify the "pessimun cement-to-aggregate ratio" of some aggregates. Most aggregates gave the highest expansion with 1:1 ratio, as far as cement-to-aggregate ratios used in this study were concerned.

### 2.3. Mixing and molding procedure

The mixing and molding procedures followed the requirements of CSA A23.2-25A. The mixing water and cement were placed in the bowl and mixed at slow speed for 30 s; the entire quantity of aggregate was then added slowly over 30 s, while mixing at slow speed. The mixture was then mixed for 30 s at medium speed and then allowed to stand for 90 s with the bowl covered with a wet towel to avoid moisture loss. The mixture was then mixed again for 60 s at medium speed.

The mixture was compacted into the molds with a tamper. The molds, covered with plastic sheet, were stored in a fog room at 23 °C for 24 ± 2 h. The bars were then demolded and immersed in water in sealed plastic containers, which were then placed in an oven at 80 °C for 24 ± 2 h. The initial length measurement is then taken, the bars transferred in containers filled with a 1 M NaOH solution at 80 °C and the containers returned to the oven maintained at 80 °C. The length changes of the bars were monitored at 1, 3, 5, 7, 10, 12, 14, 21 and 28 days, respectively. The expansion result is the average of three measurements.

The main difference between the CAMBT and the modified CAMBT in this paper is the aggregate particle size. The preliminary curing procedure adopted in both the CAMBT and the modified CAMBT, i.e. 24 h in water, is the same as in the AMBT, which is also different from the 4-h period in the 1 M NaOH solution in the original CAMBT (Table 1).

Table 2
Aggregates used in the study

| Aggregate | Origin |
|---|---|
| PH | Phonolite, Quebec, Canada |
| RG | River gravel, New South Wales, Australia |
| MQ | Quartzite, Minnesota, USA |
| QL | Greywacke, Queensland, Australia |
| PO | Quartzitic sandstone, Montreal, Canada |
| NQ | Quartzite, Norway |
| CO | Greywacke, Nova Scotia, Canada |
| PEN | Greywacke, Pennsylvania, USA |
| NRS | Reddish sandstone, Norway |
| SPH | Greywacke, New Brunswick, Canada |
| RE | Devitrified acidic tuff, Queensland, Australia |

## 3. Results and discussions of laboratory testing

Table 3 summarizes the expansion results for the different sets of concrete prisms and accelerated mortar bar tested in the study.

### 3.1. Expansion in CPT and AMBT

The one-year measured expansion of concrete prisms made with the selected aggregates and their 14-day expansions in the AMBT are plotted in Figs. 1 and 2, respectively.

As shown in Fig. 1, and in accordance with the classification proposed in CSA A23.2-27A [18], PH and RG aggregates are considered non-reactive, MQ and QL are moderately-reactive aggregates, and PO, NQ, PEN, CO, NRS, SPH, and RE are highly-reactive aggregates. However, the reactivity characteristics of aggregates based on expansion data in the AMBT are quite different from those in the CPT, especially in the case of aggregates RG and PO, for which the AMBT failed to correctly identify their reactivity (Fig. 2). For the other aggregates, the expansion level based on the AMBT is also very different from that in the CPT. It can be seen from Fig. 3 that there is no satisfactory correlation ($R^2 = 0.44$) between 14 days expansion in the AMBT and 1 year expansion in the CPT for these aggregates. The poor correlation between expansions in the AMBT and in the CPT has also been reported by other researchers [8–11].

### 3.2. Effect of particle size on expansion

The expansion of the CAMBT specimen containing various aggregate particle fractions is shown in Fig. 4.

Fig. 4 indicates that the expansion of bars with 0.15–0.80 mm aggregate particles basically increases linearly with time at least up to 28 days. For specimens with 1.25–2.50 mm and 2.5–5.0 mm particles, the expansion

Table 3
Expansion results for the concrete prisms and accelerated mortar bars

| Aggregate | CPT | AMBT | CAMBT | | | Modified CAMBT | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 year | 14 days | 0.15–0.80 mm | | | 1.25–2.50 mm | | | | 2.5–5.0 mm | | |
| | | | 10 days | 14 days | 28 days | 7 days | 10 days | 14 days | 28 days | 10 days | 14 days | 28 days |
| PH | 0.027 | 0.056 | 0.010 | 0.015 | 0.022 | – | – | – | – | – | – | – |
| RG | 0.035 | 0.310 | 0.112 | 0.197 | 0.473 | 0.072 | 0.125 | 0.200 | 0.423 | 0.078 | 0.124 | 0.324 |
| MQ | 0.094 | 0.265 | 0.106 | 0.179 | 0.422 | 0.109 | 0.179 | 0.268 | 0.512 | 0.125 | 0.181 | 0.316 |
| QL | 0.120 | 0.342 | 0.155 | 0.251 | 0.519 | 0.141 | 0.201 | 0.272 | 0.537 | 0.134 | 0.156 | 0.321 |
| PO | 0.130 | 0.093 | 0.044 | 0.057 | 0.151 | 0.105 | 0.171 | 0.239 | 0.450 | 0.138 | 0.183 | 0.312 |
| NQ | 0.150 | 0.185 | 0.074 | 0.104 | 0.235 | 0.117 | 0.175 | 0.243 | 0.447 | 0.139 | 0.185 | 0.297 |
| PEN | 0.167[a] | 0.357 | 0.165 | 0.261 | 0.563 | 0.123 | 0.181 | 0.248 | 0.483 | 0.132 | 0.172 | 0.308 |
| CO | 0.196 | 0.420 | 0.138 | 0.188 | 0.450 | 0.148 | 0.226 | 0.326 | 0.614 | 0.169 | 0.221 | 0.385 |
| NRS | 0.210 | 0.337 | 0.201 | 0.298 | 0.561 | 0.214 | 0.294 | 0.389 | 0.614 | 0.185 | 0.242 | 0.366 |
| SPH | 0.217 | 0.463 | 0.184 | 0.257 | 0.486 | 0.197 | 0.285 | 0.305 | 0.465 | 0.188 | 0.225 | 0.359 |
| RE | 0.299 | 0.426 | – | – | – | 0.126 | 0.186 | 0.268 | 0.465 | 0.123 | 0.170 | 0.300 |

[a] J. Ideker, University of Texas in Austin, Personal communication.

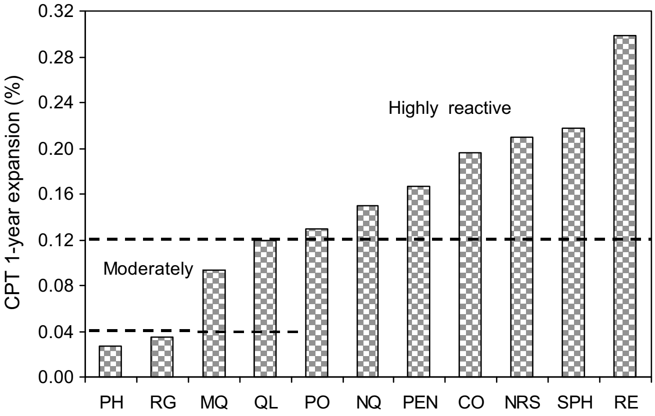

Fig. 1. One-year expansion in the CPT.

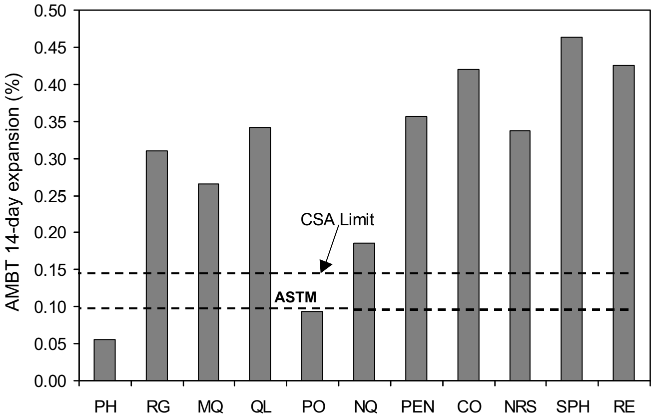

Fig. 2. 14 days expansion in the AMBT.

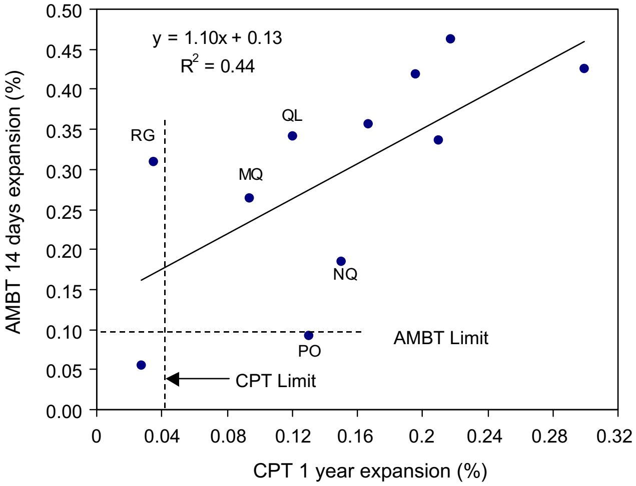

Fig. 3. Correlation of the AMBT and the CPT.

curves are generally linear, with a slow-down after about 14 days for some aggregates. The expansion behavior in CAMBT is different from that in AMBT, in which there usually has induction period or fast acceleration of expansion as the specimens begin to crack and disintegrate. Generally speaking, for specimens in CAMBT, the crack density is higher, but crack width is narrower than that in AMBT. This is mainly attributed to the difference in the cross section areas of bars and different aggregate particles sizes in AMBT and in CAMBT. After 28 days, only a few very fine cracks were noticed on the surface of specimen with 0.15–0.80 mm particles, without much gel deposition on either specimen surface or in alkali solution. Extensive visible cracks and much gel deposition on bar surface, also in alkali solution for some aggregates, were easily observed for specimen with 1.25–2.50 mm and 2.5–5.0 mm particles. Actually, for some aggregates at 1.25–2.50 mm and 2.5–5.0 mm, such as RE and SPH, gel deposition on bar surface and while materials floating in alkali solution even occurred after 3 days in alkali solution.

Measurements of mass change of the bars at 28 days showed that all the investigated aggregates gained some weight except RE (Fig. 5). Mass gain for specimens of these aggregates varies from 0.2–1.0% of their initial weights (1 day in water at 80 °C), while specimen containing RE lost about 0.4% of its weight. The weight loss of specimen with RE was probably due to the quick formation and release

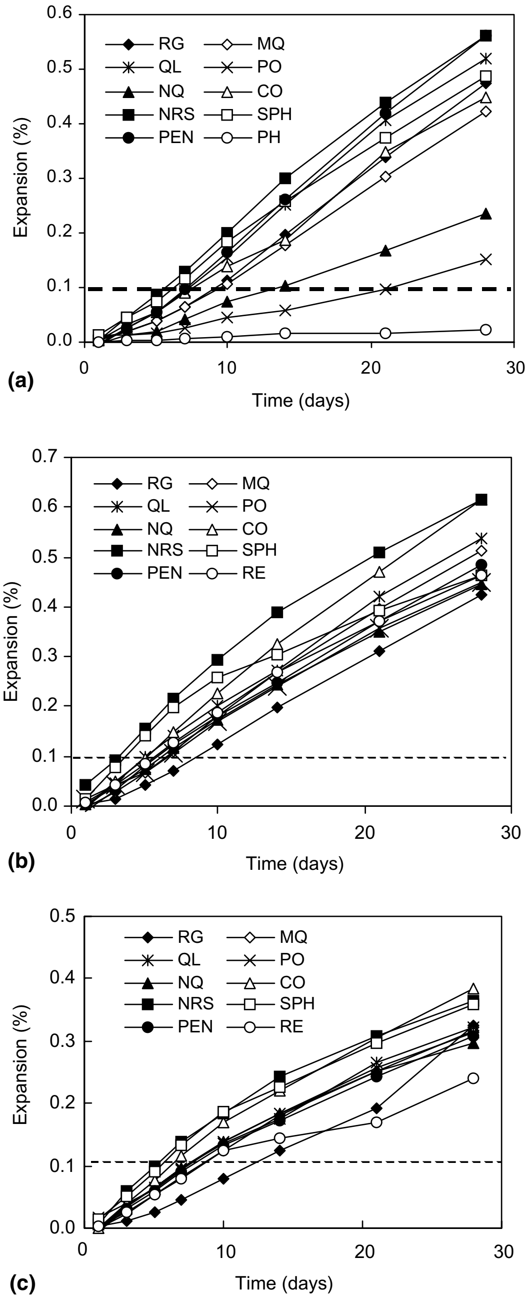

Fig. 4. Expansion curves for the CAMBT with different aggregate particle fractions: (a) 0.15–0.80 mm, (b) 1.25–2.50 mm and (c) 2.5–5.0 mm.

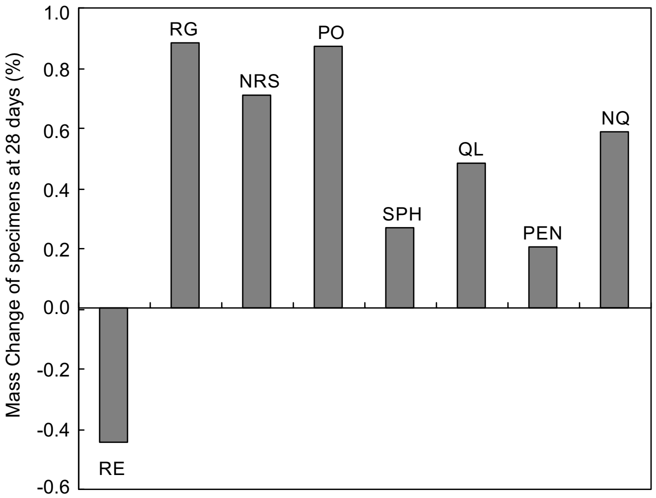

Fig. 5. Mass change of CAMBT bars with 2.5–5.0 mm aggregate particles at 28 days in NaOH solution.

into storage alkali solution of large amount of low viscosity product by the reaction of highly-reactive devitrified acidic tuff with alkalis. A detailed discussion of mass change of the specimen during the test will be the subject for future publication. But it shows here that RE seems have a different mass change pattern from other aggregates in the test conditions.

Fig. 6 shows the effect of aggregate particle size on expansion at different ages. Contrary to what was expected, the bars with the finest fraction of aggregate (e.g. 0.15–0.80 mm) did not give the largest expansion in this test condition, especially at early ages. It clearly indicates that, six of the nine aggregates gave the largest expansion at the 1.25–2.50 mm size fraction throughout the test period. Only three aggregates, i.e. RG, PEN and SPH, exhibited the highest expansion at the 0.15–0.80 mm size fraction at the later ages of 14 and 28 days. These results indicate that, for the 40 × 40 × 160 mm specimen cured in the 1 M NaOH solution at 80 °C, the finer aggregate particles, not necessarily the larger expansion.

Results in the AMBT have confirmed that for the 1 M NaOH solution at 80 °C storage regime, the cement alkali content has no significant influence on mortar bar expansion [19,20]. Although the cement, cement alkali content and the preliminary curing procedure used in this study (high-alkali cement without added alkalis, 24-h water preliminary curing) were different from that in the original proposed CAMBT (Table 1), the expansion trend of the bars should be similar in the two conditions. Using 0.10% as a criteria for expansion, as shown in Fig. 4, the bar with 0.15–0.80 mm particles could not identify the reactivity of most investigated aggregates correctly at 7 days. It failed to test the reactivity of PO even by extending the testing time to 14 days. With 2.5–5.0 mm particles, however, the reactivity of all of the tested aggregates can be recognized correctly at 10 days.

### *3.3. Discussions on the effect of aggregate particle size in accelerated tests*

Increasing the surface area of aggregate particles, increasing temperature of testing and using high-alkali system are common approaches that have been used to accelerate the reaction/expansion processes in developing accelerated tests for evaluating the potential alkali-reactivity of concrete aggregates. The present results and results from literatures [16,17] strongly suggest that, in the quest for rapid and large expansion in accelerated laboratory testing for potential alkali-aggregate reactivity by reducing

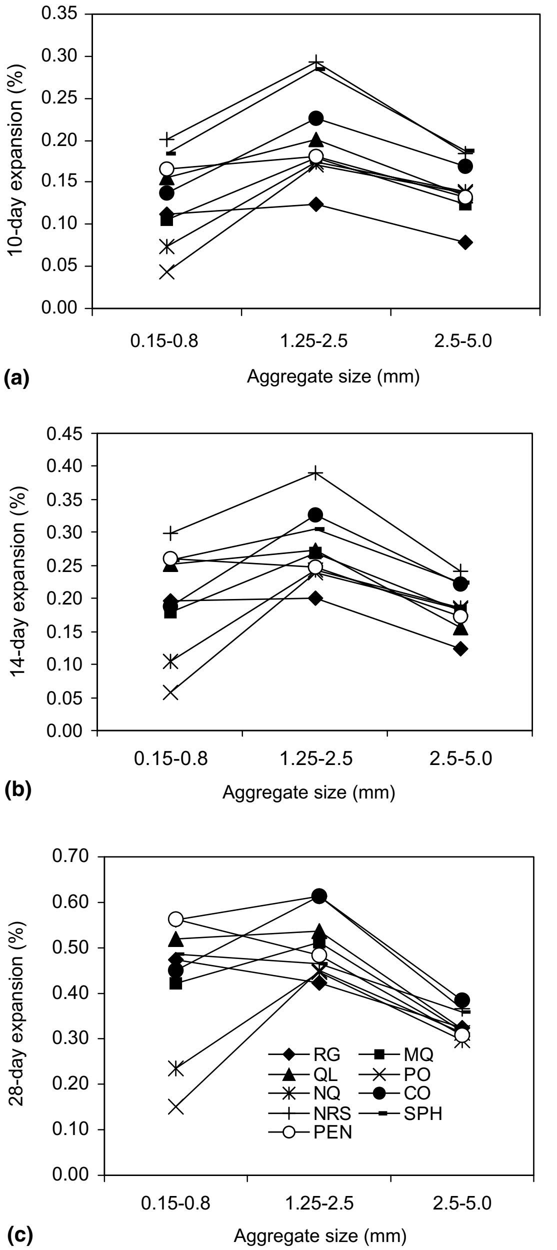

Fig. 6. Relationship between expansion and aggregate size at 10 days (a), 14 days (b) and 28 days (c).

aggregate particle size to increase the rate and degree of the reaction, attention should also be paid to the textural effect of the particles. In order to reliably determine the potential alkali-reactivity of an aggregate, and eventually to select appropriate preventive measures using an accelerated test procedure in the laboratory, any processing action performed on the aggregate tested (crushing, grinding, etc.) should, ideally, maintain its textural characteristics and relative reactivity level compared with other less, more or equally-reactive aggregates when tested in the CPT. Therefore, the very fine particles used in the AMBT and the CAMBT may not be always suitable for testing the AAR reactivity because the aggregate may lose the critical texture during processing. For instance, in the case of the Potsdam sandstone (PO) and Norwegian quartzite (NQ), the potential reactivity of the aggregate is attributed to the siliceous material cementing well-rounded quartz grains forming the bulk of the stone [21,22]. As illustrated in Figs. 3 and 4a, the two aggregates induce large expansion in the CPT but fairly low expansions in the AMBT and CAMBT compared with other aggregates with lower CPT expansion (MQ and QL). The consequence is that the two aggregates pass the AMBT and/or CAMBT but fail the CPT. This is attributed to the sample preparation process for accelerated tests (i.e. crushing/pulverizing, sieving and washing) actually eliminated a fair amount of the reactive siliceous cement of the aggregates and the characteristic texture of the rocks was also lost in the fine aggregate fractions. Indeed, as shown in Fig. 7, PO and NQ gave low expansion with 0.15–0.80 mm particles, especially at early ages before 14 days, but a high and similar expansion with particles that can maintain their original textural characteristics. The potential alkali-reactivity of the PO and NQ is correctly recognized by using the modified CAMBT with 1.25–2.50 mm or 2.5–5.0 mm aggregate particles (expansion at 10 days).

On the other hand, the RG aggregate has been used for several decades in concrete structures without inducing any deleterious expansion/cracking due to ASR. Testing performed in this study has confirmed the non-reactive character of the RG aggregate in the CPT, although the expansion at one year is close to the limit (0.035%) and expansion goes beyond the 0.04% level during the second year of testing. However, the aggregate induces large expansion in the AMBT (0.310% at 14 days). Crushing the material to produce smaller particles definitely has a strong impact on the expansion of the RG aggregate. The marginally-reactive character of the aggregate seems to be better identified using the modified CAMBT (i.e.

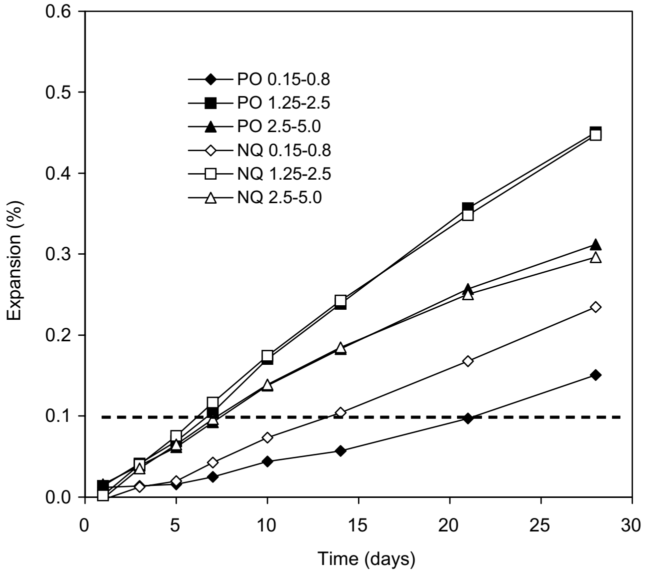

Fig. 7. Effect of aggregate particle size on expansion of bar with PO and NQ.

particle sizes of 2.5–5.0 mm), with expansions of 0.078% and 0.124% at 10 and 14 days, respectively. As mentioned before, the AMBT was often found to exaggerate the potential alkali-reactivity of concrete aggregates, which is probably due to the use of finer material and to the impact of using higher temperature on some minerals in aggregates.

### *3.4. Correlations of different accelerated tests with the CPT*

#### *3.4.1. CAMBT versus AMBT*

Figs. 8 and 9 show the correlation between the 14 days expansion in the AMBT and the 10 days and 14 days expansions in the CAMBT for the series of aggregates investigated.

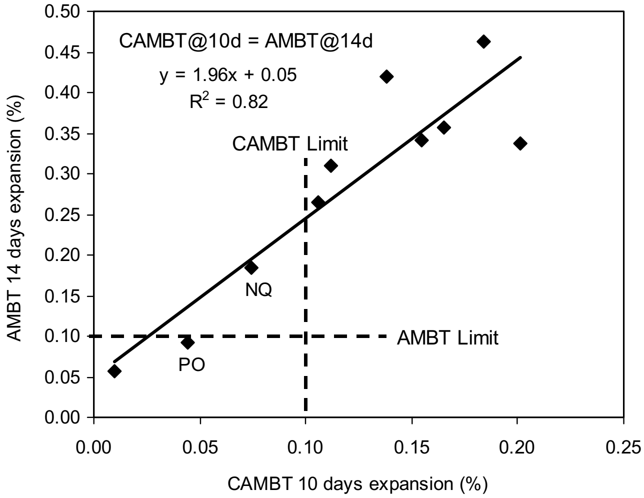

Fig. 8. 10 days expansion in the CAMBT versus 14 days expansion in the AMBT.

It shows an acceptable correlation between expansions in these two methods. However, based on the criteria of 0.10%, the two methods produced different outcomes on the expansivity of the aggregate NQ. Generally, the CAMBT gave lower expansion than the AMBT and could not identify the expansivity of NQ at 10 days. When extending the testing time to 14 days, both the CAMBT and the AMBT gave the same outcome on all aggregates investigated (Fig. 9).

The relatively good correlation between the CAMBT and the AMBT could probably be attributed to the large amount of fine aggregate particles used in these two methods.

#### *3.4.2. CAMBT versus CPT*

Similar to the AMBT (Fig. 3), as shown in Figs. 10 and 11, the CAMBT has a very poor correlation with the CPT results and it cannot satisfactorily determine the expansivity of PO and NQ aggregates after the 10-day testing period (Fig. 10). The reactive characteristic of NQ was detected when extending test time to 14 days (Fig. 11), but same as in the AMBT, the expansion of RG was overestimated at 14 days.

The 1.25–2.50 mm fraction generally induces the largest bar expansion of the three size fractions tested, especially at early ages (Fig. 6). Fig. 12 shows that modified CAMBT with 1.25–2.50 mm aggregate particles can identify the reactivity of the investigated aggregates within 7 days based on 0.1% criteria for expansion. However, the correlation of the expansion between the modified CAMBT with 1.25–2.50 mm particles and the CPT is very poor ($R^2 = 0.36$). The correlation is greatly improved as shown in Fig. 13, when the RE was excluded ($R^2 = 0.74$, expansion limit 0.07% is calculated from the trend line equation).

As illustrated in Fig. 14, using a 0.08% expansion level as the acceptance criteria in the modified CAMBT with

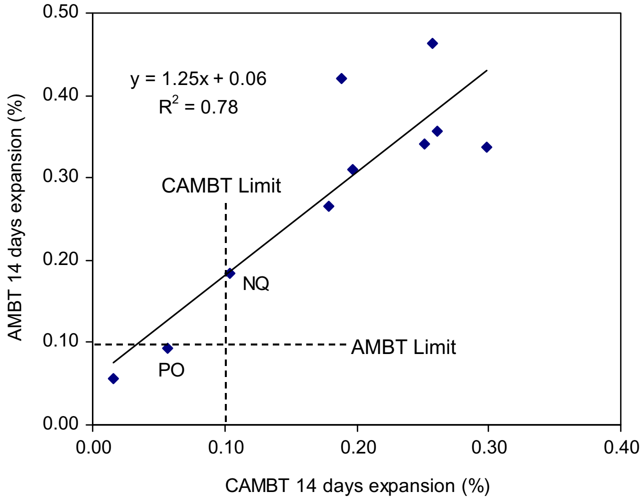

Fig. 9. 14 days expansion in the CAMBT versus 14 days expansion in the AMBT.

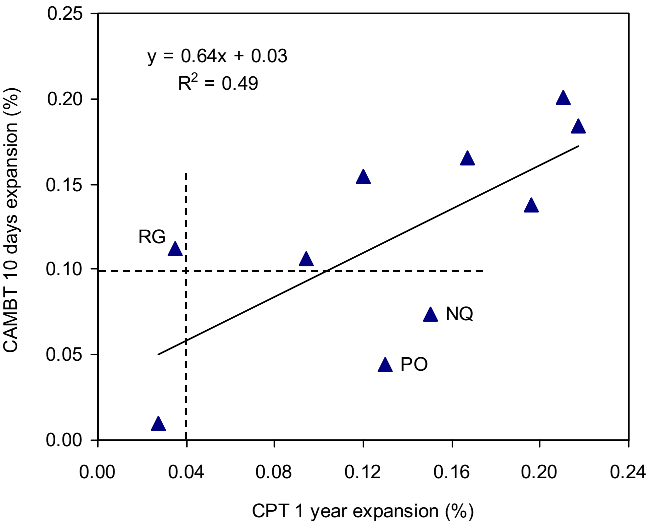

Fig. 10. CAMBT 10 days expansion (with 0.15–0.8 mm fraction) versus CPT 1 year expansion.

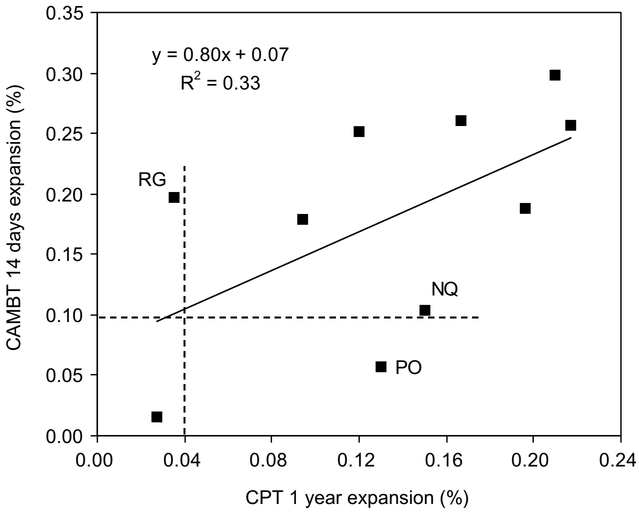

Fig. 11. CAMBT 14 days expansion (with 0.15–0.8 mm fraction) versus CPT 1 year expansion.

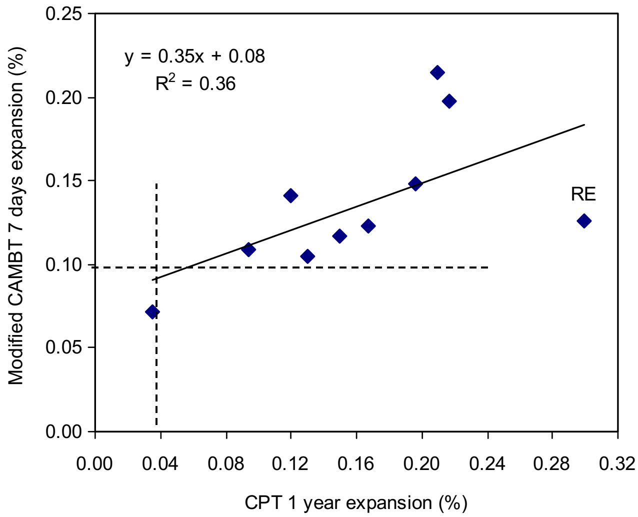

Fig. 12. Modified CAMBT with 1.25–2.50 mm aggregate particles versus the CPT.

2.5–5.0 mm particle size (0.08% is calculated from the trend line equation), the reactivity of aggregates based on 10 days expansion is in agreement with the CPT, although RE gave a low expansion relative to the CPT. Furthermore, the correlation coefficient of expansions between the modified CAMBT with 2.5–5.0 mm size fraction and the CPT ($R^2 = 0.88$) for aggregates other than RE is also satisfactory. It means that the bar incorporating 2.5–5.0 mm particle size aggregate can not only identify the reactivity of these aggregates within a shorter time than the AMBT, but it seems to also recognize the degree of reactivity of different aggregates. As discussed previously, the "abnormal" expansion behavior of RE is probably due to the formation and release of lots of low viscosity ASR product into alkali solution. More aggregates from different origins and with different microstructural characteristics will be tested to verify the criteria and the correlation with the CPT.

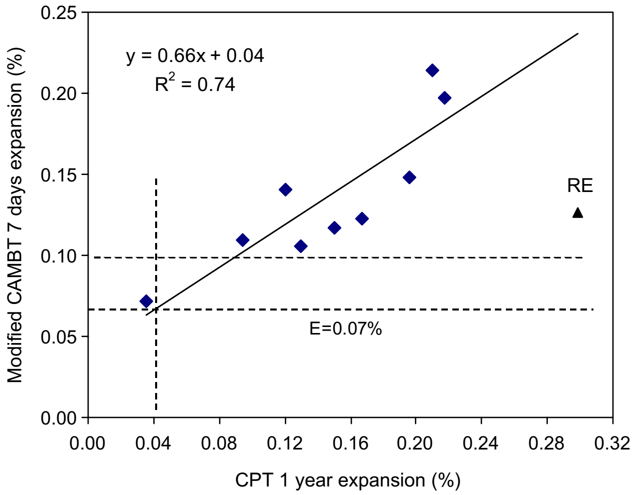

Fig. 13. Modified CAMBT with 1.25–2.50 mm aggregate particles versus the CPT (RE excluded).

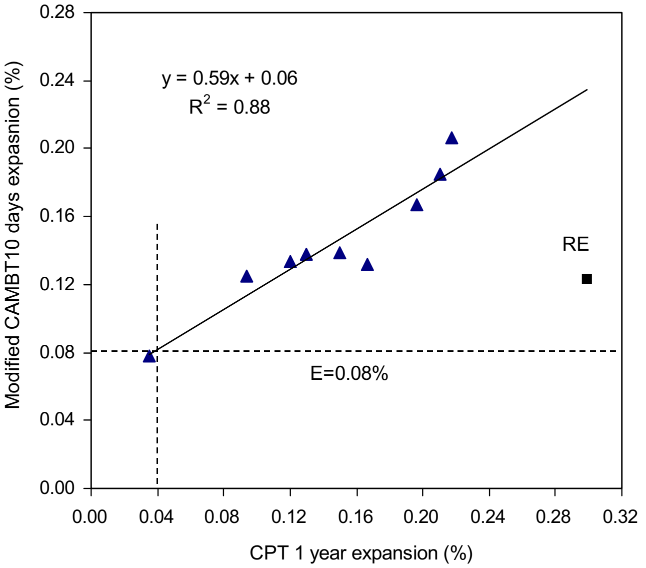

Fig. 14. Modified CAMBT with 2.5–5.0 mm aggregate particles versus CPT.

## 4. Conclusions

From the expansion results of mortar bars incorporating various aggregates of different sizes, the 0.15–0.80 mm size range is not the size fraction inducing largest expansion in the 40 × 40 × 160 mm bars immersed in a 1 M NaOH solution at 80 °C, especially at an early period before 10 days. For the large majority of aggregates tested, the 1.25–2.50 mm size fraction gave the highest expansion during the first 14 days.

Correlation between the CAMBT and the AMBT is relatively good, probably because they both use a large proportion of fine aggregate particles. However, the correlations in expansions of both the AMBT and the CAMBT with the CPT are very poor. The best correlation obtained was 10 days expansion of modified CAMBT containing 2.5–5.0 mm aggregate particles with the 1 year expansion in the CPT. The use of a single 2.5–5.0 mm single size aggregate fraction shows promise as a quick test to evaluate the potential alkali-silica reactivity of aggregates, but further tests are necessary to establish the full reliability of the test.

## 5. Recommendations for future research

According to a recent publication [23], it is possible to use a modified CAMBT with 4.75–12.5 mm aggregate particles to test both alkali-carbonate reactivity and alkali-silica reactivity of concrete aggregate. However, it needs 30 days of testing in a 1 M NaOH solution, and the correlation with the CPT was not satisfactory for another suite of aggregates [24]. For alkali-carbonate reactive aggregates, compared with the 5–10 mm particle size, the 2.5–5.0 mm fraction also gave considerable expansion, especially during the early 4-week curing period [25]. More aggregates from different origins, including both ASR and ACR aggregates, will be used to verify the reliability of using modified CAMBT with 2.5–5.0 mm aggregate fraction as a universal test for potentials of both alkali-silica and alkali-carbonate reactivity of concrete aggregates.

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## References

[1] ASTM C 1260-94. Standard test method for determining the potential alkali reactivity of combinations of cementious materials and aggregate (accelerated mortar-bar method). Annual Book of ASTM Standards 2002, vol. 04.02, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

[2] CSA A23.2-25A-00. Detection of alkali-silica reactive aggregate by accelerated expansion of mortar bars. CSA A23.2-00: Methods of Test for Concrete, Canadian Standards Association, Mississauga (ON).

[3] RILEM TC191-ARP-AAR02: Detection of potential alkali-reactivity of aggregates—the ultra-accelerated mortar-bar test. Mater Struct 2000;33:283–93.

[4] Oberholster RE, Davies G. An accelerated method for testing the potential alkali reactivity of siliceous aggregates. Cem Concr Res 1986;16:181–9.

[5] CSA A23.2-14A-00. Potential expansivity of aggregates (procedure for length change due to alkali-aggregate reaction in concrete prisms). CSA A23.2-00: Methods of Test for Concrete, Canadian Standards Association, Mississauga (ON), 2000. p. 207–16.

[6] ASTM C 1293-01. Standard test method for concrete aggregates by determination of length change of concrete due to alkali-silica reaction. Annual Book of ASTM Standards, vol. 04.02 (Concrete and Aggregates), Philadelphia (PA), 2002.

[7] Nixon PJ. RILEM TC-106-AAR: Alkali-aggregate reaction-recommendations-B-TC106-3 (now AAR-3)-detection of potential alkali-reactivity of aggregates-methods for aggregate combinations using concrete prisms. Mater Struct 2000;33(229):290–3.

[8] Bérubé M-A, Fournier B, Mongeau P, Dupont N, Ouellet C, Frenette J. Effectiveness of the accelerated mortar method. ASTM C-9 proposal P214 or NBRI, for assessing potential AAR in Quebec (Canada). In: Proc 9th international conference on alkali-aggregate reaction in concrete, London, 1992. p. 92–109.

[9] Fournier B, Bérubé M-A. Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications. Can J Civil Eng 2000;27(2):167–91.

[10] DeMerchant DP, Fournier B, Strang F. Alkali-aggregate research in New Brunswick. Can J Civil Eng 2000;27(2):212–25.

[11] de Grosbois M, Fontaine E. Evaluation of the potential alkali-reactivity of concrete aggregates: performance of testing methods and a producer's point of view. In: Proc 11th international conference on alkali-aggregate reaction, Quebec, 2000. p. 267–76.

[12] Tang Mingshu, Han Sufen, Zheng Shihua. A rapid method for identification of alkali reactivity of aggregate. Cem Concr Res 1983;13(3):417–22.

[13] Criaud A, Vernet C, Defosse C. The microbar method, an accelerated expansion test for evaluating aggregates—assessment of Canadian aggregates. Canadian Developments in Testing Concrete Aggregates for Alkali-Aggregate Reactivity, Ministry of Transportation, Ontario. Engineering Materials Report 92, 1990. p. 201–14.

[14] Xu Zhongzi, Shen Yang, Lu Duyou, et al. Main parameters in the new test method for alkali-silica reactivity. J Nanjing Univ Chem Technol 1998;20(2):1–7.

[15] Hobbs DW, Gutteridge WH. Particle size of aggregate and its influence upon the expansion caused by the alkali-silica reaction. Mag Concr Res 1979;31(109):235–42.

[16] Lu Duyou, Xu Zhongzi, Tang Mingshu. ASR model for aggregate with different microstructure and texture. J Chin Silicate Soc 2002;30(2):149–54.

[17] Rivard P, Fournier B, Ballivy G. The damaging rating index method for ASR affected concrete—a critical review of the petrographic features of deterioration and evaluation. Cem Concr Aggr 2002;24(2):1–11.

[18] CSA A23.2-27A-00. Standard practice to identify degree of alkali-reactivity of aggregates and to identify measures to avoid deleterious expansion in concrete. CSA A23.2-00: Methods of Test for Concrete, Canadian Standards Association, Mississauga (ON), 2000. p. 251–9.

[19] Hooton RD, Rogers CA. Development of the NBRI rapid mortar bar test leading to its use in North America. In: Proc 9th international conference on alkali-aggregate reaction in concrete, London, vol. 1, 1992. p. 461–7.

[20] Hooton RD. Inter-laboratory study of the NBRI rapid test method and CSA standardization status. Canadian Developments in Testing Concrete Aggregates for Alkali-Aggregate Reactivity, Ontario Ministry of Transportation, Engineering Materials Report 92, 1990. p. 225–40.

[21] Bérubé M-A. Expansion test methods for mass concrete exposed to alkali-aggregate reaction, vol. 1. Final report for CEA project 715 G 687, 1992, Canadian Electrical Association, Montreal (Canada), 99p.

[22] Jensen V, Fournier B. Influence of different procedures on accelerated mortar and concrete prism tests: assessment of seven Norwegian alkali-reactive aggregates. In: Proc 11th international conference on alkali-aggregate reaction, Quebec, 2000. p. 345–54.

[23] Grattan-Bellew PE, Cybansk G, Fournier B, Mitchell L. Proposed universal accelerated test for alkali-aggregate reaction. The concrete microbar test. Cem Concr Aggr 2004;25(1):29–34.

[24] Grattan-Bellew PE, Lu Duyou, Fournier B, Mitchell L. Comparison of expansions in the concrete prism and concrete microbar tests of in assorted suite of aggregates from several countries. In: Proc 12th international conference on alkali-aggregate reaction, Beijing, 2004. p. 251–6.

[25] Xu Zhongzi, Lan Xianghui, Deng Min, Tang Mingshu. An accelerated test method for alkali-carbonate reactivity. In: Proc 11th international conference on alkali-aggregate reaction, Quebec, 2000. p. 129–38.