Construction and Building Materials

Reliability of AMBT and CPT in testing the effectiveness of SCM to mitigate alkali-silica reaction of field concrete

--Manuscript Draft--

Manuscript Number:	CONBUILDMAT-D-22-00930R3
Article Type:	Research Paper
Keywords:	Alkali-silica reactivity, AMBT, ASR, CPT, performance limits, supplementary cementitious material
Corresponding Author:	Marie Joshua Tapas University of Technology Sydney AUSTRALIA
First Author:	Vute Sirivivatnanon, Ph.D.
Order of Authors:	Vute Sirivivatnanon, Ph.D.
	Paul Thomas, Ph.D.
	Marie Joshua Tapas, Ph.D.
	Thuc Nguyen, Ph.D.
Abstract:	This paper examines the reliability of the Australian Standard accelerated mortar bar test (AMBT) and concrete prism test (CPT), AS 1141.60.1 and 60.2, respectively, and the potential for extending these standard test methods to the determination of the type and dosage of supplementary cementitious materials (SCMs) required to mitigate deleterious alkali-silica reaction (ASR) in a similar manner to the corresponding ASTM C1567 and CSA A23.2-28A. Both AMBT and CPT have their strengths and limitations, however, their overwhelming value is in the availability of laboratory test results and their correlation with long-term performance (up to 20 years) of large concrete blocks and structural elements. Since Australia has no existing field exposure site, this paper uses reported data from CANMET's and Ontario Hydro's outdoor exposure sites in Ottawa and Kingston, respectively, in Canada and the 18-year exposure site data from the BRE site in the UK to demonstrate the efficacy of the AMBT and CPT approaches to evaluation of ASR reactivity and ASR mitigation using SCM blended cements. Good correlations are observed for moderately-reactive and highly reactive aggregates used with low-alkali cement and cement with alkali contents up to 0.9% Na2Oeq. The assessment of reported research demonstrates that both AMBT and CPT have the capacity to predict the long-term performance of structural concrete. In addition, AMBT and 2-year CPT test results for eight Australian reactive aggregates are reported showing the influence of SCMs on mitigation of expansion. Whilst both AMBT and CPT demonstrated their potential for assessing SCMs in mitigation of ASR, AMBT was found to be more conservative than CPT and higher SCM dosages were required to achieve a non-reactive classification. The accelerated test data reported coupled with the correlation of AMBT and CPT to the prediction of long term performance of concretes strongly supports the extension of the Australian test methods AS 1141.60.1 and 60.2 for the assessment of ASR mitigation using SCMs.
Suggested Reviewers:	Jason Ideker Professor, Oregon State University jason.ideker@oregonstate.edu ASR expert
	Douglas Hooton Professor Emeritus, University of Toronto hooton@civ.utoronto.ca ASR expert
	Ahmad Shayan ARBB ash17492@bigpond.net.au Australian ASR expert

	Benoit Fournier Professor, Laval University: Universite Laval benoit.fournier@ggl.ulaval.ca ASR expert
	Børge Johannes Wigum Norwegian University of Science and Technology borgejohannes.wigum@heidelbergdement.com former RILEM ASR TC chair; ASR expert

University of Technology Sydney (UTS)
15 Broadway Ultimo NSW 2007
January 12, 2023

Prof. Michael C. Forde
Editor-in-Chief
Construction and Building Materials

Dear Prof. Forde,

On behalf of all my co-authors, I am writing to address the comment of Reviewer 1 on the manuscript we submitted to Construction and Building Materials entitled **"Reliability of AMBT and CPT in testing the effectiveness of SCM to mitigate alkali-silica reaction of field concrete".**

In this paper, the possible extension and the reliability of the Australian Standard accelerated mortar bar test (AMBT) AS 1141.60.1 and concrete prism test (CPT) AS 1141.60.2 to determine the type and dosage of supplementary cementitious materials (SCMs) required in mitigating the potential alkali-silica reactivity (ASR) of a range of aggregates have been examined. Since Australia has no field exposure site, this paper uses reported data from CANMET's and Ontario Hydro's outdoor exposure sites in Ottawa and Kingston, Canada and the 18-year exposure site data from the BRE site in the UK to demonstrate the efficacy of the AMBT and CPT approaches to evaluation of ASR reactivity and ASR mitigation using SCM blended cements.

The changes made in the manuscript (3rd revision) in response to the comments of Reviewer 1 are highlighted in **BLUE**. A separate response to reviewer document is also attached. We hope that you find our response to the review sufficient and consider our manuscript for publication.

Thank you for the opportunity to contribute to this journal. We are grateful for the time spent by all the reviewers in making sure that our journal paper is published with highest quality.

Respectfully,

Dr Marie Joshua Tapas
BS Materials Engineering, MSc., PhD
Research Associate, University of Technology Sydney

Co-authors:

Vute Sirivivatnanon, PhD (first author)
Professor and UTS-Boral Centre for Sustainable Building Director
School of Civil and Environmental Engineering, University of Technology Sydney
Email: vute.sirivivatnanon@uts.edu.au

Paul Thomas
Senior Lecturer
School of Civil and Environmental Engineering, University of Technology Sydney
Email: paul.thomas@uts.edu.au

Thuc Nhu Nguyen
Research Associate
School of Civil and Environmental Engineering, University of Technology Sydney
Email: Thuc.Nguyen@uts.edu.au

Reliability of AMBT and CPT in testing the effectiveness of SCM to mitigate alkali-silica reaction of field concrete

Vute Sirivivatnanon[a], Paul Thomas[a], Marie Joshua Tapas[a,*] and Thuc Nhu Nguyen[a]
[a]School of Civil and Environmental Engineering, University of Technology Sydney

Abstract

This paper examines the reliability of the Australian Standard accelerated mortar bar test (AMBT) and concrete prism test (CPT), AS 1141.60.1 and 60.2, respectively, and the potential for extending these standard test methods to the determination of the type and dosage of supplementary cementitious materials (SCMs) required to mitigate deleterious alkali-silica reaction (ASR) in a similar manner to the corresponding ASTM C1567 and CSA A23.2-28A. Both AMBT and CPT have their strengths and limitations, however, their overwhelming value is in the availability of laboratory test results and their correlation with long-term performance (up to 20 years) of large concrete blocks and structural elements. Since Australia has no existing field exposure site, this paper uses reported data from CANMET's and Ontario Hydro's outdoor exposure sites in Ottawa and Kingston, respectively, in Canada and the 18-year exposure site data from the BRE site in the UK to demonstrate the efficacy of the AMBT and CPT approaches to evaluation of ASR reactivity and ASR mitigation using SCM blended cements. Good correlations are observed for moderately-reactive and highly reactive aggregates used with low-alkali cement and cement with alkali contents up to 0.9% Na_2O_{eq}. The assessment of reported research demonstrates that both AMBT and CPT have the capacity to predict the long-term performance of structural concrete. In addition, AMBT and 2-year CPT test results for eight Australian reactive aggregates are reported showing the influence of SCMs (fly ash and slag) on mitigation of expansion. Whilst both AMBT and CPT demonstrated their potential for assessing SCMs in mitigation of ASR, AMBT was found to be more conservative than CPT and higher SCM dosages were required to achieve a non-reactive classification. The accelerated test data reported coupled with the correlation of AMBT and CPT to the prediction of long term performance of concretes strongly supports the

extension of the Australian test methods AS 1141.60.1 and 60.2 for the assessment of ASR mitigation using SCMs.

Keywords: Alkali-silica reactivity, AMBT, ASR, CPT, performance limits, supplementary cementitious material

*Corresponding author: mariejoshua.tapas@uts.edu.au

1. Introduction

There are two common alkali-silica reactivity (ASR) test methods namely the accelerated mortar bar test (AMBT) and concrete prism test (CPT). The AMBT and CPT have been standardised in many national standards and used widely as listed below:

AMBT: ASTM C1260 [1], CSA A23.2-25A [2], RILEM AAR-2 [3], and AS 1141.60.1 [4]

CPT: ASTM C1293 [5], CSA A23.2-14A [6], RILEM AAR-3 [7] , and AS 1141.60.2 [8]

The AMBT and CPT have also been adopted to determine the type and dosage of supplementary cementitious materials (SCMs) required in mitigating the potential alkali-silica reaction (ASR) in concrete. The most commonly applied are the ASTM C1567 [9] and CSA A23.2-28A [10].

Thomas and Innis [11] stressed that the usefulness of various tests may be judged on the basis of (i) the ease of testing, (ii) the repeatability or precision of the outcomes, (iii) the time taken to complete the test and, ultimately, (iv) the ability of the test to predict behaviour in the field.

Both AMBT and CPT are fairly simple test methods. AMBT requires 2-3 weeks of testing while CPT requires a full year to determine the potential reactivity of an aggregate or 2 years to determine the effectiveness of a supplementary cementitious material (SCM) to mitigate ASR. The reliability of the two test methods for assessing the efficacy of SCMs in ASR mitigation or which among the two is a better test method however remain in question. CPT which in theory provides a finite supply of alkali, although widely reported as the more accurate laboratory test method [12], was found to be prone to alkali leaching leading to inconsistencies in expansion results [13-15]. Since ASR expansion is influenced by the amount of alkalis present in the pore solution, leaching of alkalis over time can lead to variability in expansion results, underestimation of expansion and even to the determination of much lower dosages of SCMs required for effective mitigation if leached alkalis cannot be accounted for [12-15]. AMBT, on the other hand, although was found by Fournier et al. [16] to have better precision than the CPT is heavily criticized due to the infinite supply of alkali and the use of high testing temperature (1M NaOH at 80 °C) [12]. Since both test methods remain controversial and there are conflicting results reported in literature, undoubtedly the most challenging requirement is their accuracy to predict the effectiveness of SCM in mitigating ASR of field concrete. This can only be assessed from well-kept record of test results and long-term evaluation of real structures or field-exposed large concrete blocks and structural elements.

1.1 Reliability of AMBT and CPT in evaluating the reactivity of aggregate consistent with field performance

The Australian AMBT AS 1141.60.1 and CPT AS 1141.60.2 adopted test procedures correspondingly from ASTM 1260 and ASTM C1293 with different performance limits leading to a new class of slowly reactive aggregates in the case of AMBT AS1141.60.1. The expansion limits for AMBT are listed in Table 1. For the CPT, AS 1141.60.2 specifies an expansion limit of 0.03% compared to the 0.04% used in the corresponding ASTM C1293 and CSA 23.2-14A test method.

Table 1 Comparison of ASTM and AS accelerated mortar bar expansion limits

ASTM C1260		AS 1141.60.1		
Interpretation	14 days	Classification	10 days	21 days
Innocuous	< 0.10%	Non-reactive	-	< 0.10%*
Uncertain	0.10 to 0.20%	Slowly reactive	< 0.10%*	≥0.10%* and < 0.30%
Potential deleterious	≥ 0.2*%	Reactive	≥ 0.10%* or	≥ 0.30%

* For naturally occurring fine aggregates the limit is 0.15%

The reliability of Australian AMBT and CPT test methods in predicting ASR of field concrete has been compiled and examined by Sirivivatnanon et al. [17]. It was found from the international and Australian research data that AMBT was an excellent screening test for non-reactive aggregates and to correctly classify 'reactive' aggregates consistent with field performance with few exceptions. The concrete prism test was found to be more reliable as it correctly classified almost all 64 aggregates against known field performance.

In this paper, the extension of the Australian AMBT and CPT method to determine the effectiveness of SCM in mitigating ASR expansion, similar to the ASTM C1567 and CSA A23.2-28A, respectively, is examined. In particular, the reliability of these laboratory test methods in determining the dosage of SCM for ASR mitigation consistent with reported field concrete performance is examined from a collection of long-term (18-20 years) exposure concrete specimens at CANMET Ottawa (Canada), Ontario Hydro & MTO Kingston (Canada) and BRE Watford exposure site (UK).

2. Experimental Program

A total of 8 aggregates were tested to both the Australian AMBT AS 1141.60.1 and CPT AS 1141.60.2. Two types of supplementary cementitious materials (SCMs): fly ash and slag; were used. The fly ashes and slags, provided by suppliers from various states/regions in Australia, comply with

AS 3582.1 (Supplementary Cementitious Materials Part 1: Fly Ash) [18] and AS 3582.2 (Supplementary Cementitious Materials Part 1: Slag-Ground granulated blast furnace) [19], respectively. AS 3582.1 requires fly ash to have SiO_2+Al_2O_3+Fe_2O_3≥70% while AS 3582.2 specifies maximum 15% MgO and 18% Al_2O_3 in the slag. Moreover, as recommended by SA HB 79 "Alkali-Aggregate Reaction-Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia" [20], fly ashes and slags used in this testing program have total alkali content ≤3% Na_2O_{eq} and ≤1% Na_2O_{eq} respectively. All fly ashes have CaO ≤8%. A number of Type GP cements complying with AS 3972 (General Purpose and Blended Cements) [21], were also used. All cements used for the AMBT and CPT testing program have an alkali content ≤0.6% Na_2O_{eq}. The source of GP cement and SCMs was chosen according to their availability in the location of individual aggregate. Thus, the outcomes of these tests are highly relevant to the usage of the aggregates.

Testing was conducted in three commercial laboratories in Australia. The AMBT and CPT tests per set of aggregates and SCMs were only carried out once (i.e. by a single laboratory and therefore the testing program was not similar to a proficiency test). The results reported in this manuscript are therefore combined results from the three participating laboratories. This was agreed as the most practical approach since the AMBT and CPT tests were carried out as part of a commercial program participated by the aggregate and SCM suppliers in Australia under the leadership of Cement Concrete and Aggregates Australia (CCAA). The choice of which aggregates and SCMs to test depends on their availability in the Australian region and therefore means that if fly ash for instance is more abundant in the region, then it is the SCM that was tested in the program.

2.1 Extension of Australian Test Methods for Mitigation

AS 1141.60.1 test procedure is similar to ASTM C1260 and was used to test the effectiveness of various SCMs in mitigating ASR similar to ASTM C1567. Comparison will be made in the use of the respective criteria in AS 1141.60.1 (see Table 1) and ASTM C1567 to gauge the efficacy of SCM. ASTM C1567 specifies that expansion of less than 0.10 % at 14 days AMBT bath exposure indicates a low risk of deleterious expansion when used in concrete under field conditions while expansion of more than 0.10 % at 14 days is indicative of potentially deleterious expansion.

AS 1141.60.2 test procedures, which are similar to ASTM C1293 and Canadian Standard CSA A23.2-14A, were used to determine the length change of concrete due to ASR with an extended testing period from one year to two years for combinations of cementitious materials for mitigation determination. Comparison will be made in the use of the respective criterion in AS 1141.60.2, ASTM C1293 or CSA A23.2-28A in gauging the efficacy of the SCM.

3. Experimental Results

3.1 Alkali-Silica Reactivity by AMBT and CPT

The 10, 14 and 21-day AMBT expansion results and 1-year CPT expansion results of all 8 aggregates are tabulated in Table 2. It is worth noting that whereas the tests were conducted in accordance with AS standards, ASTM C1778 (Table 4) was used to classify the aggregate reactivity of the CPT test results. This is just to provide a wider range of reactivity classification as opposed to just reactive (≥0.03%) and non-reactive classification (<0.03%) in AS AS1141.60.2. Highly reactive aggregates notably require higher SCM dosage for effective mitigation than moderately reactive aggregates as shown in Table 3.

Results in Table 2 show that similar rock type from different quarries, such as the two meta greywacke aggregates can exhibit very different susceptibility to alkali-silica reactivity (ASR) determined from the expansion tests. Moreover, the degree of reactivity of each aggregate, determined from AMBT, may differ from that determined from the CPT. In Table 2, it can be seen that a basalt and a quartz are found to be reactive by the AMBT but non-reactive by the CPT. CPT results have been found to be more reliable and consistent with long-term field performance [17].

Table 2 AMBT and CPT Expansion Results for Aggregate Reactivity

	Aggregate	AS1141.60.1 AMBT				AS1141.60.2 CPT	
		10-day	14-day	21-day	AS1141.60.1 Classification	1-year	ASTM C1778 Classification
1	Dacite	0.35	0.47	0.64	Reactive	0.233	Highly R
2	Rhyolite	0.24	0.35	0.47	Reactive	0.142	Highly R
3	Meta Greywacke	0.23	0.34	0.49	Reactive	0.158	Highly R
4	Quartz	0.09	0.15	0.27	Slowly-R	0.003	Non-R
5	Hornfels	0.17	0.27	0.40	Reactive	0.070	Moderate R
6	Rhyodacite	0.23	0.32	0.43	Reactive	0.059	Moderate R
7	Meta Greywacke	0.23	0.30	0.39	Reactive	0.053	Moderate R
8	Basalt	0.52	0.73	1.05	Reactive	0.007	Non-R

3.2 Type and dosage of SCM required to mitigate ASR

Table 3 shows the summary of AMBT and CPT results for ASR mitigation. Testing of the effectiveness of SCM to mitigate ASR commenced following the availability of AMBT results for aggregate reactivity and prior to the completion of CPT. Thus, basalt and quartz aggregates which are both reactive in AMBT but not in CPT were still tested with various dosages of fly ash using both test methods. From Table 3, it was found that both fly ash and slag are effective in mitigating ASR with a range of 15-25% fly ash and 30-50% slag required to mitigate ASR depending on the aggregate and its reactivity. Further, it is notable that higher dosages of fly ash are required to mitigate ASR for ASTM C1778 [22] highly reactive (HR) aggregates than moderately reactive (MR) aggregates.

The reliability of these short-term laboratory tests in predicting long-term field performance will be evaluated and discussed in Section 4. It should be noted that the AMBT always gives similar or more conservative SCM dosages for mitigation than the CPT. Amongst the two AMBT methods, AS 1141.60.1 requires similar or more conservative SCM dosage than ASTM C1567.

As outlined in the methology, since the expansion results from the AMBT and CPT tests reported in Tables 2 and 3 are combined results from the three participating laboratories with one aggregate+SCM combination tested only by a single laboratory (i.e. testing was not carried out similar to a proficieny test), the spread of data is not possible to report. This was agreed as the most practical approach since the AMBT and CPT tests were carried out as part of a commercial program participated by various aggregate and SCM suppliers in Australia. The choice of which aggregate and SCM combination to test depends on their availability in the Australian region.

Table 3 Summary of AMBT and CPT expansion results for ASR Mitigation

Aggregate	Type	%	AMBT Expansion (%)			Classification		CPT Expansion (%)		Classification	
			10 d	14d	21 d	ASTM C1567	AS1141 60.1	1 Y	2 Y	CSA A23.2-28A	AS1141 60.2
Dacite	Eraring Flyash	0.0	0.35	0.47	0.64	R	R	0.233	-	R	R
		10.0	0.11	0.18	0.29	R	R	0.080	0.148	R	R
		15.0	0.03	0.06	0.11	N	SR	0.008	0.022	N	N
		25.0	0.01	0.01	0.02	N	N	-0.002	0.001	N	N
Rhyolite	Eraring Flyash	0.0	0.24	0.35	0.47	R	R	0.142	-	R	R
		10.0	0.04	0.07	0.12	N	SR	0.001	0.005	N	N
		15.0	0.02	0.03	0.04	N	N	-0.005	-0.003	N	N
		25.0	0.01	0.01	0.02	N	N	-0.006	0.001	N	N
Meta Greywacke	Central Qld Flyash	0.0	0.23	0.34	0.49	R	R	0.158	-	R	R
		10.0	0.10	0.19	0.30	R	R	0.058	0.115	R	R
		15.0	0.04	0.08	0.15	N	SR	0.021	0.046	R	R
		25.0	0.01	0.02	0.04	N	N	0.005	0.011	N	N
Quartz	Central Qld Flyash	0.0	0.09	0.15	0.27	R	R	0.003	-	N	N
		10.0	0.03	0.06	0.13	N	SR	-0.003	0.007	N	N
		15.0	0.01	0.03	0.05	N	N	-0.004	-0.003	N	N
		25.0	0.00	0.01	0.01	N	N	-0.008	-0.007	N	N
Hornfels	ICL Slag	0	0.17	0.27	0.40	R	R	0.070	0.155	R	R
		30.0	0.10	0.17	0.27	R	R	-0.006	0.013	N	N
		40.0	0.04	0.07	0.13	N	SR	-0.023	-0.011	N	N
		50.0	0.02	0.03	0.04	N	N	-0.011	-0.003	N	N
Rhyodacite	Mt Piper Flyash	0.0	0.23	0.32	0.43	R	R	0.059	0.087	R	R
		15.0	0.06	0.09	0.15	N	SR	0.002	0.010	N	N
		22.5	0.02	0.03	0.04	N	N	-0.006	-0.003	N	N
		30.0	0.02	0.02	0.02	N	N	-0.006	-0.001	N	N
Meta Greywacke	Sunstate Flyash	0	0.23	0.30	0.39	R	R	0.053	0.122	R	R
		15.0	0.03	0.04	0.07	N	N	-0.017	-0.009	N	N
		20.0	0.02	0.03	0.03	N	N	-0.006	-0.001	N	N
		25.0	0.01	0.02	0.02	N	N	-0.007	-0.009	N	N
Basalt	Eraring Flyash	0	0.52	0.73	1.05	R	R	0.007	0.024	N	N
		15.0	0.05	0.08	0.21	N	SR	-0.009	-0.007	N	N
		22.5	0.02	0.02	0.05	N	N	-0.010	-0.005	N	N
		30.0	0.01	0.02	0.02	N	N	-0.014	-0.009	N	N

AS1141.60.1 & 60.2 Classification: N - non reactive, SR – slowly reactive, R – reactive.
ASTM C1567 & CSA A23.2-28A Classification: N – non reactive, R – reactive.

4. Reliability of AMBT and CPT in predicting ASR mitigation of field concrete

In this paper, the extension of AMBT and CPT methods to determine the effectiveness of SCMs in mitigating ASR expansion, such as the ASTM C1567 and CSA A23.2-28A respectively will be examined. In particular, the reliability of these laboratory test methods in determining the dosage of SCM for ASR mitigation consistent with field concrete will be determined from inspection of published long-term (18-20 years) exposure concrete test data at CANMET Ottawa Canada, Ontario Hydro & MTO Kingston Canada and BRE Watford UK exposure site [23-26]. Data from other exposure sites are not considered as they are usually short-term exposure.

4.1 Correlation between short-term laboratory and field exposure

The extent of alkali-silica reaction in concrete depends largely on the reactivity of aggregate, the level of alkali and the environmental conditions such as the temperature and relative humidity. The reactivity of aggregate has been classified from petrographic examination and the expansion from the standard AMBT and CPT. ASTM C1778 [22] or AASHTO PP65 [27] classification of aggregate reactivity is reproduced in Table 4. ASTM C1778 or AASHTO PP65 are not test methods but rather guide for reducing the risk of deleterious alkali-aggregate reaction in concrete. Based on the expansion results obtained from test methods ASTM C1260 and ASTM C1293, ASTM C1778 classifies aggregate reactivity into four "aggregate reactivity classes". Based on the reactivity classification, the risk levels are assessed and required levels of prevention are identified.

The alkali in concrete is largely derived from the Portland cement and reference is made to low-alkali (LA) cement and high-alkali (HA) cement. In this paper, LA cement and HA cement are defined in terms of their sodium oxide equivalent (Na_2O_{eq}) of no greater than 0.6% and greater than 0.8% respectively.

Table 4 ASTM C1778 & AASHTO PP65 classification of aggregate reactivity

Aggregate-Reactivity Class	Description of Aggregate Reactivity	1-Year Expansion in Test Method ASTM C1293, %	14-Day Expansion in Test Method ASTM C1260, %
R0	Non-reactive	<0.04	<0.10
R1	Moderately reactive	≥0.04, <0.12	≥0.10, <0.30
R2	Highly reactive	≥0.12, <0.24	≥0.30, <0.45
R3	Very highly reactive	≥0.24	≥0.45

A range of concretes manufactured from moderately and highly reactive aggregates with both LA and HA cement has been tested in the laboratory as well as large concrete blocks or structural elements in the field [23-26]. In most cases, the performance of the field-exposed concrete has been reported in terms of expansion and cracking. Expansion within 0.05% is associated with non-deleterious deterioration. The results of laboratory tests and their correlation with long-term performance (up to 20 years) of large concrete blocks and structural elements at CANMET's and Ontario Hydro's outdoor exposure sites in Ottawa and Kingston in Canada, and the 18-year exposure site data from the BRE site in the UK are examined.

4.2 CANMET outdoor exposure site

Fournier et al. [23] showed that low-alkali cement can be used to limit the deleterious expansion of concrete blocks up to 15-year exposure at CANMET outdoor exposure site in Ottawa, Canada. These blocks were manufactured from 4 different moderately-reactive aggregates, one highly-reactive and one very extremely-reactive aggregate. There is a good correlation of short-term laboratory tests to long-term 15-year field performance of concrete manufactured from high-alkali 0.9% Na_2O_{eq} cement and 20% fly ash for four moderately-reactive aggregates. There was one exception with a Canadian argillaceous limestone which showed deleterious expansion even with 10% SF. All concretes made from three Australian aggregates and low-alkali cement without SCM showed non-deleterious expansion in the field exposed blocks (Table 5). Fournier et al. reported some discrepancies in the outcomes of CPT (with high-alkali cement) and large concrete blocks results where freeze and thaw conditions existed as in the case of CANMET exposure site.

Fournier et al. [24] provided laboratory AMBT and CPT results and corresponding long-term 20-year field performance of concrete blocks manufactured mainly from high-alkali cement (0.9% Na_2O_{eq}) and SCM (fly ash, slag and silica fume) with one moderately reactive Sudbury gravel (Su) and one highly reactive Spratt limestone aggregate (Sp). The blocks were exposed at CANMET outdoor exposure site in Ottawa, Canada. Block expansion above 0.05% was deemed to be deleterious expansion. The results are compiled in Table 6. In addition to the concrete blocks with the inherent alkali from the cement, companion concrete blocks containing added alkali were also exposed to see the effect of higher alkali and SCM on long-term performance. The expansion results of the concrete blocks boosted with alkali are not reported in this paper since they are not relevant to Australian context. Australian cement has a low alkali limit of 0.6%Na_2O_{eq} and therefore field expansion results of blocks made with up to 0.9% Na_2O_{eq} alkali cement are already sufficient to address the objectives of the work.

Table 5 Correlation of short-term laboratory tests to long-term 15-year field performance at CANMET outdoor exposure site in Ottawa, Canada (concretes with inherent alkali from cement) [23]

Detail of aggregates	Agg	AMBT	CPT		SCM	Cement	Block expansion ≤0.05% @15year
		14 days	1 year	2 year			
Moderately reactive aggregates							
Gr Granite and granitic gneiss, Canada	Gr	NA	NA	-	0	Low-alkali	√
Rg Granitic gravel, Australia	Rg	NA	NA	-	0	Low-alkali	√
Al Sandstone, greywacke, mudstone, volcanic gravel, Canada	Al	0.36	0.09	-	0	Low-alkali	√
Lm Argillaceous limestone, Canada	Lm	NA	NA	-	0	Low-alkali	No
Su Sandstone, quartzwacke, arkose, greywacke and argillite, Canada	Su	0.278	0.075	-	0	Low-alkali	√
Su Sandstone, quartzwacke, arkose, greywacke and argillite, Canada	Su	0.048	-	0.003	20%FA	0.9% Na_2O_{eq}	√
Al Sandstone, greywacke, mudstone, volcanic gravel, Canada	Al	0.037	-	0.007	20%FA	0.9% Na_2O_{eq}	√
Ed Sandstone, claystone, chart gravel, Canada	Ed	0.023	-	0.022	20%FA	0.9% Na_2O_{eq}	√
Gr+ Granite and granitic gneiss, Canada	Gr+	NA	-	NA	20%FA	0.9% Na_2O_{eq}	√
Lm Argillaceous limestone, Canada	Lm	NA	-	NA	10%SF	0.9% Na_2O_{eq}	No
Highly reactive and Extremely reactive aggregates							
Ql Greywacke, Australia	Ql	NA	NA	-	0	Low-alkali	√
Re Mixed volcanic, Australia	Re	NA	NA	-	0	Low-alkali	√

NA = not available, S = ggbfs; FA = fly ash (ASTM Class F), SF = silica fume, √ = block expansion ≤0.05%.

Table 6 Laboratory AMBT and CPT expansion compared to the status of large concrete blocks after 20-year exposure at CANMET Ottawa outdoor exposure site [24]

Aggregate	AMBT	CPT		SCM	Alkali in Cement % Na_2O_{eq}	Na_2O_{eq} Kg/m^3	Block expansion ≤0.05% @20year	Field consistent with lab tests
	14 days	1 year	2 year					
Su	0.278	0.157	-	0	0.4% Na_2O_{eq}	1.68	√	No
Su	0.278	0.157	-	0	0.9% Na_2O_{eq}	3.78	No	Yes
Su	0.140	-	0.034*	35%S	0.9% Na_2O_{eq}	2.46	No	Yes*
Su	0.043	-	0.014	50%S	0.9% Na_2O_{eq}	1.89	√	Yes
Su	0.048	-	0.008	20%FA	0.9% Na_2O_{eq}	3.02	√	Yes
Su	0.021	-	0.007-	30%FA	0.9% Na_2O_{eq}	2.65	√	Yes
Su	0.112	-	0.030*	7.5%SF	0.9% Na_2O_{eq}	3.50	No	Yes*
Su	0.078	-	0.023	10.0%SF	0.9% Na_2O_{eq}	3.40	No	No
Su	0.052	-	0.009	12.5%SF	0.9% Na_2O_{eq}	3.31	√	Yes
Sp	0.391	0.207	-	0	0.4% Na_2O_{eq}	1.68	No	Yes
Sp	0.391	0.207	-	0	0.9% Na_2O_{eq}	3.78	No	Yes
Sp	0.190	-	NA	35%S	0.9% Na_2O_{eq}	2.46	No	Yes, AMBT
Sp	0.066	-	0.014	50%S	0.9% Na_2O_{eq}	1.89	√	Yes
Sp	0.103	-	NA	20%FA	0.9% Na_2O_{eq}	3.02	No	Yes, AMBT
Sp	0.032	-	0.005	30%FA	0.9% Na_2O_{eq}	2.65	√	Yes
Sp	0.180	-	NA	7.5%SF	0.9% Na_2O_{eq}	3.50	No	Yes, AMBT
Sp	0.142	-	0.038*	10%SF	0.9% Na_2O_{eq}	3.40	No	Yes*

*designates the use of Australian CPT expansion limit of 0.03% rather than 0.04% limit in CSA 23.2-28A.
S = ggbfs; FA = fly ash (ASTM Class F), SF = silica fume, NA = not available, √ = block expansion ≤0.05%.

With both the moderately-reactive Sudbury gravel and highly-reactive Spratt limestone aggregate with high-alkali 0.9% Na_2O_{eq}, there is an outstanding consistency between AMBT, CPT and the large concrete blocks with no added alkali especially if the Australian CPT limit of 0.03% was used for expansion at one year (without SCM) and two years (with SCM) instead of the 0.04% expansion limit used in ASTM C1293 or CSA 23.2-28A. When both AMBT and CPT showed effective mitigation from an SCM, the corresponding concrete blocks showed no deleterious expansion greater than 0.05% after 20-year exposure. On the other hand, when both AMBT and CPT showed an amount of SCM to be ineffective in mitigating the alkali-silica reaction in one or both laboratory tests, the corresponding concrete blocks showed deleterious expansion greater than 0.05%. Interestingly for concrete with SCM, even with no CPT results available, AMBT has shown to be a consistent indicator of field performance as shown in the Spratt limestone concrete with 7.5%SF, 20%FA and 35%S mixes.

There is one exception to this general finding for Sudbury gravel where both AMBT and CPT showed 10% silica fume to be effective in mitigating the alkali-silica reaction whereas the large concrete block displayed deleterious expansion after 20 years field exposure. This mix has high alkali at 3.4 kg/m^3 of Na_2O_{eq}. It should also be noted that the low alkali (0.4% Na_2O_{eq}) cement without any SCM is proven effective in preventing deleterious expansion of the large concrete blocks with the moderately-reactive Sudbury gravel, but is ineffective for the highly-reactive Spratt limestone.

The results from Fournier et al. [24] field exposure would suggest excellent correlation between laboratory tests and 20-year field performance when cement with alkali content up to 0.9% Na_2O_{eq} is used. Australian cement has a maximum allowable alkali content of 0.6% Na_2O_{eq} so the data examined provide significant information for current Australian practice.

Kerenidis & Hooton [28] studied the mitigation of ASR in high-alkali cement concretes with SCM. They experimented with three cements with inherent alkali contents of 0.97%, 1.08% and 1.13% Na_2O_{eq} using either fly ash or slag. The cement alkali content was adjusted to 1.25% Na_2O_{eq} as per CPT standard. Results of the study shown in Figure 1 demonstrate that all the fly ash or slag cement replacement levels, selected from CSA A23.2-27A, were effective in controlling deleterious expansions for both Spratt (highly reactive) and Sudbury (moderately reactive) aggregates when tested according to CSA A23.2-28A. From the results, they suggested that it appeared unnecessary to increase the cement alkali content above 1.25% Na_2O_{eq} for testing. It should be noted that while the inherent alkali content in the cement does not affect the outcomes based on the expansion criterion of 0.04%, it can significantly influence the magnitude of CPT expansion in concrete mixes without SCM. The effect is less significant in mixes with SCM. In the same study, Kerenidis & Hooton [28] also compared the AMBT and CPT results to confirm that AMBT results are more conservative than the CPT results in terms of the required mitigation dosage of fly ash or slag consistent with the observation in Table 3.

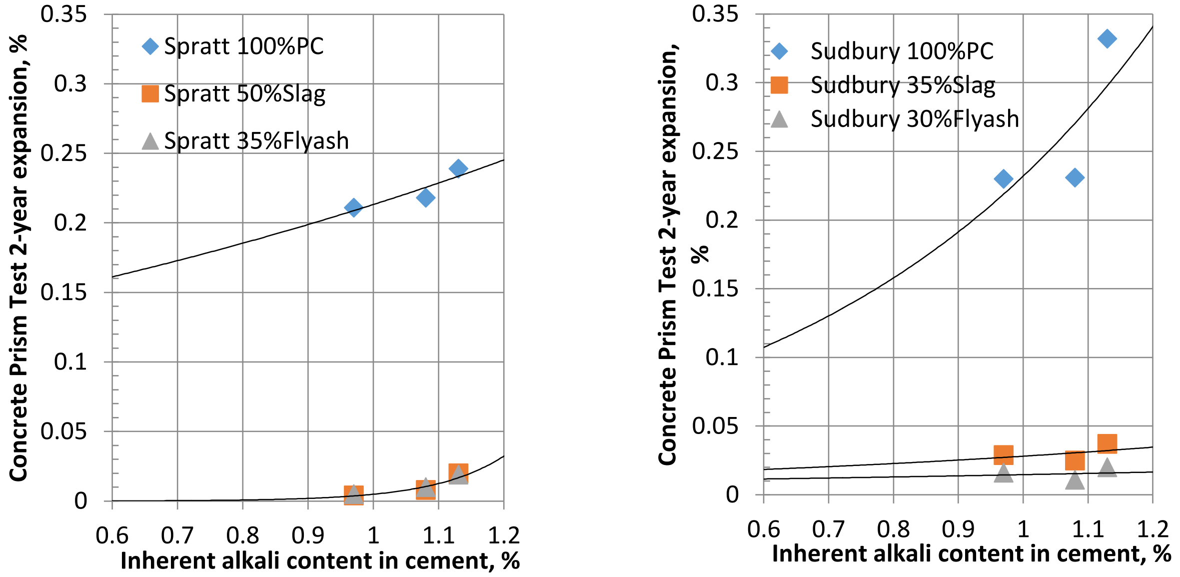

Fig. 1. Effect of cements' inherent alkali content on 2-year expansion of concrete with the same 1.25% Na_2O_{eq} in CPT [28]

4.3 MTO Kingston exposure site

Hooton et al. [25] demonstrated a correlation between short-term laboratory AMBT tests to long-term 20-year field performance of concrete beams and slabs manufactured from a high-alkali cement with and without a range of SCMs and a highly reactive Spratt limestone. This correlation can be extended to their CPT results if the Australian CPT limit of 0.03% was used (Table 7). Two mixes pass both AMBT & CPT tests to show non-deleterious expansion and show less than 0.05% expansion in the field specimens after 20 years exposure. Two other mixes fail both AMBT & CPT (Australian CPT limit of 0.03%) and show deleterious expansion (>0.05%) in the field specimens. In the case of mixes without SCM, the reactive aggregate showed AMBT 14-day expansion greater than 0.1% for mixes with low-alkali and high-alkali cement, consistent with field exposed concrete beams and slab expanding greater than 0.05% after 20-year exposure at MTO Kingston exposure site.

Table 7 Laboratory AMBT and CPT expansion compared to the status of unreinforced and reinforced concrete beams and slabs after 20-year exposure at an outdoor exposure site in Kingston [25]

Mix	AMBT	CPT		SCM	Cement $\%Na_2O_{eq}$	Na_2O_{eq} kg/m^3	UR beam ≤0.05% @20year	R beam ≤0.05% @20year	Slab ≤0.05% @20year	Field consistent with lab tests
	14 days	1 year	2 year							
1	0.059	<<0.03	<0.03	50%S	0.79%	1.65	<0.05	<0.05	<0.05	Yes
2	0.111	<0.03	0.037	18%FA	0.79%	2.72	>0.05	>0.05	>0.05	Yes*
3	0.187	<0.03	0.045	25%S	0.79%	2.48	>0.05	>0.05	>0.05	Yes*
4	0.041	<<0.03	<0.03	25%S, 3.8%SF	0.79%	2.36	<0.05	<0.05	<0.05	Yes
5	0.435	<0.03	0.04	0	0.48%	2.00	>0.05	>0.05	>0.05	Yes AMBT
6	0.315	0.13	0.15	0	0.79%	3.30	>0.05	>0.05	>0.05	Yes

*designates the use of Australian CPT expansion limit of 0.03% rather than 0.04% limit in CSA 23.2-28A.
S = ggbfs; FA = fly ash (ASTM Class F), SF = silica fume, UR = unreinforced, R = reinforced.
CPT expansions are read off from Fig. 2 in Hooton et al. (2013) [25]

Hooton et al. [25] concluded that when high-alkali cement was replaced with 50% slag or 25% slag + 3.8% silica fume interground with a high-alkali Portland cement, there was no sign of ASR or cracking after 20 years exposure. The findings in Table 7 demonstrated the consistency between the expansion of field concretes with the laboratory AMBT and CPT results provided that the Australian CPT expansion limit of 0.03% at 2 years for concrete with SCM was used.

4.4 BRE outdoor exposure site near Watford, UK

Thomas et al. [26] examined the effectiveness of two sources of fly ash in mitigating deleterious expansion of two sizes of large concrete blocks for up to 18 years exposure at BRE outdoor exposure site near Watford, UK. Three reactive flint sands and one highly reactive greywacke coarse and fine aggregates were tested with a high-alkali (1.15% Na_2O_{eq}) cement. Concrete with a range of binder contents, as controls and with 25% and 40% fly ash, were tested in both AMBT and non-standard CPT. Results with one fine fly ash (FF, 3.4%LOI, 8.0% >45 µm) are compiled in Table 8. Thomas et al. [26] concluded that the results clearly showed the effectiveness of fine fly ash in controlling the expansion of the concrete blocks consistent with the available AMBT and non-standard concrete prisms with no boosted alkali and cured at 38°C (no expansion results reported). There were exceptions with two flint-bearing mixes made with a relatively coarse FA and high alkali contents.

Table 8 BRE outdoor exposure site study of the effectiveness of fly ash in ASR mitigation in concrete blocks and cubes after 18-year exposure [26]

Aggregate	AMBT 14-day	SCM	Binder content	Na_2O_{eq} kg/m^3	Block expansion ≤0.05% @18year	Field consistent with lab tests	Note
TV, BT, PB	-	0%FF	550	6.33	No	-	No lab test results
	-	25%FF	550	4.74	√	-	No lab test results
	-	40%FF	550	3.80	√	-	No lab test results
TV, BT, PB	-	0%FF	475	5.46	No	-	No lab test results
	-	25%FF	475	4.09	√	-	No lab test results
	-	40%FF	475	3.28	√	-	No lab test results
TV, BT	0.34-0.40	0%FF	412	4.74	No	Yes	
	0.06-0.08	25%FF	400	3.45	√	Yes	
	0.02	40%FF	400	2.76	√	Yes	
GW	-	0%FF	450	5.18	No*	-	Extensive cracking width up to 5mm
	-	25%FF	450	3.88	√*	-	No cracking
	-	0%FF	350	4.03	No*	-	Light cracking width up to 1mm
	-	25%FF	360	3.11	√*	-	No cracking

TV: Thames Valley river sand 50% flint, BT: Crushed sand 55% flint and quartz, PB: Sea-dredge sand similar composition to TV, GW: Grey-wacke highly reactive coarse & fine, FF: Fly ash 3.4%LOI 8.0% >45 µm.

Thomas and Innis (1999) [11] published data from 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 CPT and the 14-day expansion in AMBT. 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 0.04% limit at 2 years in the CPT.

5. Discussion

In this study, reported data from CANMET's and Ontario Hydro's outdoor exposure sites in Canada and the 18-year exposure site data from the BRE site in the UK were examined against laboratory results to investigate the efficacy of the AMBT and CPT approaches to evaluate aggregate reactivity and ASR mitigation using SCM blended cements. The results of this study demonstrate that there is a strong correlation between AMBT, CPT and field exposure data up to an exposure period of 20 years, particularly, when CPT AS 1141.60.2 limit of 0.03% is used. It is notable that the AS CPT limit is more conservative than the ASTM C1293/CSA 23.2-28A limit of 0.04% at 2 years which has proven useful in correctly classifying ASR potential consistent with field performance. Australian AMBT AS 1141.60.1 is also notably more conservative than ASTM C1567 as it has a 21-day expansion limit of 0.10% to be deemed non-reactive in comparison to ASTM's 0.10% expansion limit at 14 days. Since ASTM C1567 showed very good correlation to field performance (Tables 5-8), this suggests that AS 1141.60.1 will also perform to similar capacity. This is further supported by data in Table 3 which show that amongst the two AMBT methods, AS 1141.60.1 requires similar or more conservative SCM dosage than ASTM C1567. Based on the results of this study, Australian standards for assessing aggregate reactivity, AS 1141.60.1 and AS 1141.60.2, have the potential to be extended for use in assessing the efficacy of SCMs in ASR mitigation.

Several researchers have argued against the reliability of the AMBT and CPT tests because of their reported limitations [12]. In the case of CPT, leaching is the biggest concern and although several studies have focused on reducing the leaching in CPT, the issue remains unresolved [29, 30]. Whereas, the focus of recent studies is on perfecting the test methods, it should be noted that these tests were developed to assess aggregate reactivity and SCM efficacy in very specific conditions and the limits were established based on correlation/benchmarking with field exposure data. This means that in the case of CPT for example, if the test is carried out precisely according to the standard in the manner that the standard is benchmarked, then the leaching of alkalis is accounted for. However, as the test is empirical (i.e. by correlation or benchmarking), any change to the method makes the limits invalid and new limits will need to be defined by a thorough benchmarking program. Alternatively, the test limits can also be changed to accommodate existing field data similar to the Australian CPT limit (i.e. AS expansion limit of 0.03% is adopted rather than 0.04% so that the CPT test correlates with field exposure tests). This is an adjustment of the threshold based on an empirical observation by correlation with published long-term field performance data.

Another important outcome of this study is the expansion results of the 8 Australian aggregates in Table 3 showing that AMBT provides either similar or more conservative dosage than CPT when used to determine the dosage of SCM required to mitigate ASR and even a more accurate indicator of field performance than CPT as shown in Table 6. Moreover, Tables 6 and 8 also show that AMBT is as accurate when it is the only standard laboratory test available. This is likely because whereas CPT in theory contains a fixed amount of alkali, the available alkali in the pore solution is reduced over time due to leaching [12, 13], hydration reactions (i.e. binding of the alkalis in the hydration products especially when SCMs are incorporated in the binder) [31-33], and formation of ASR products [32, 34]. AMBT on the other hand, provides excessive 1M NaOH alkali supply to sustain ASR and replenish the alkalis consumed in the mortar. The continuous supply of alkali in the mortar makes AMBT a more conservative test method for assessing the required SCM dosage for ASR mitigation. This however also implies how critical the proper identification of expansion limits are by benchmarking to ensure that SCM dosages determined from the test are not overly conservative. A study of ASTM C1567 has reported that extending the duration of the test to 28 days as oppose to the 14-day limit is overly conservative and results in estimates of much higher levels of SCM (by 1.5 times on average) to control expansion than that actually required in the field [13].

The review of the correlation of these laboratory tests and long-term field performance data fully support the adoption of these Australian standards and corresponding expansion limits to determine the type and dosage of SCM required to mitigate ASR in the long term. Based from evaluated data, these findings are applicable to cement with alkali contents up to 0.90% Na_2O_{eq}. Australian cement currently has maximum allowable alkali content of 0.60% Na_2O_{eq} and therefore these results provide valuable information for current Australian practice.

6. Conclusions on the reliability of AMBT and CPT in predicting field performance

This paper examined the possible extension of the Australian AMBT and CPT to determine the effectiveness of SCMs in mitigating ASR expansion. Extensive laboratory accelerated tests (AMBT and CPT) were carried out in Australia and assessed with respect to the compilation of the correlation between laboratory accelerated tests and long-term performance (≥15 years) of field exposed large concrete blocks or structural elements at CANMET Ottawa Canada, Ontario Hydro & MTO Kingston Canada and BRE Watford UK exposure. All AMBT and CPT tests carried out in Australia made use of cement with alkali content ≤0.60% Na_2O_{eq} and SCMs complying with Australian standards AS 3582.1 (fly ash) and AS 3582.2 (slag). Fly ashes and slags were sourced from various parts of Australia and have total alkali content ≤3% Na_2O_{eq} and ≤1% Na_2O_{eq} respectively as recommended by SA HB 79 “Alkali-Aggregate Reaction-Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia”. All fly ashes contain ≤8% CaO. The conclusions of the study are outlined below.

1. Australian standards AMBT and CPT correlate well with the long-term performance of field concrete with SCM up to an exposure period of 20 years for concrete made with cement with alkali content of up to 0.90% Na_2O_{eq}. This is particularly the case when the Australian CPT expansion limit of 0.03% at 2 years is used instead of the 0.04% expansion limit used in the ASTM and Canadian standards. Australian cement has a maximum allowable alkali content of 0.60% Na_2O_{eq} and therefore, these findings are applicable and valuable to the mitigation of ASR in Australia.
2. AMBT has proven to be a more accurate indicator of field performance than CPT if there were conflicting results between the two laboratory tests as shown in Table 6. AMBT is as accurate when it is the only standard laboratory test available such as in the case of concrete tested at the BRE and CANMET Ottawa outdoor exposure sites (Tables 6 and 8).
3. In determining the effectiveness of SCMs (fly ash and slag) in mitigating ASR, the AMBT requires a similar or more conservative dosage of SCM than the CPT. Amongst the 2 AMBTs, AS 1141.60.1 has been found to require a similar or more conservative dosage of SCM than ASTM C1567.
4. These findings support the extension of both Australian test methods AS 1141.60.1 (AMBT) and AS 1141.60.2 (CPT) for mitigation based on the existing expansion criteria but with an extended period of 2 years for the CPT.

The data examined in this study, to the authors' best knowledge, are the only available long-term data (≥15 years) existing in literature. It is also worth noting that Australia has no existing field exposure site and hence, this study made use of field exposure data from other parts of the world to demonstrate the efficacy of the Australian AMBT and CPT approaches to the evaluation of ASR mitigation using SCM blended cements.

Acknowledgement

This study is funded through the Australian Research Council Research Hub for Nanoscience-Based Construction Materials Manufacturing (NANOCOMM) with the support of Cement Concrete and Aggregates Australia (CCAA).

References

[1] ASTM International, ASTM C1260 Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), West Conshohocken, Pennsylvania, United States, 2014.
[2] Canadian Standards Association, CSA A23.2-25A Test method for detection of alkali-silica reactive aggregate by accelerated expansion of mortar bars, Ontario, Canada.
[3] P.J. Nixon, I. Sims, RILEM Recommended Test Method: AAR-2—Detection of Potential Alkali-Reactivity—Accelerated Mortar-Bar Test Method for Aggregates, in: P.J. Nixon, I. Sims (Eds.), RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS, Springer Netherlands, Dordrecht, 2016, pp. 61-77.
[4] Standards Australia, AS 1141.60.1 Methods for sampling and testing aggregates Method 60.1: Potential Alkali-Silica Reactivity-Accelerated Mortar Bar Method, Standards Australia Limited, Sydney, Australia, 2014.
[5] ASTM International, ASTM C1293 Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction, ASTM International, West Conshohocken, Pennsylvania, United States, 2020.
[6] Canadian Standards Association, CSA A23.2-14A Expansivity of Aggregates; Procedure for Length Change Due to Alkali-Aggregate Reaction in Concrete Prisms, Ontario, Canada.
[7] P.J. Nixon, I. Sims, RILEM Recommended Test Method: AAR-3—Detection of Potential Alkali-Reactivity—38 °C Test Method for Aggregate Combinations Using Concrete Prisms, in: P.J. Nixon, I. Sims (Eds.), RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS, Springer Netherlands, Dordrecht, 2016, pp. 79-97.
[8] Standards Australia, AS 1141.60.2 Methods for Sampling and Testing Aggregates Method 60.2: Potential Alkali-Silica Reactivity-Concrete Prism Method, Standards Australia Limited, Sydney, Australia, 2014.
[9] ASTM International, ASTM C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method), West Conshohocken, Pennsylvania, United States, 2013.
[10] Canadian Standards Association, CSA A23.2-28A Standard practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete, Ontario, Canada, 2009.
[11] M.D.A. Thomas, F.A. Innis, Use of the Accelerated Mortar Bar Test for Evaluating the Efficacy of Mineral Admixtures for Controlling Expansion due to Alkali-Silica Reaction, Cement, Concrete and Aggregates 21(2) (1999).

[12] M. Thomas, B. Fournier, K. Folliard, J. Ideker, M. Shehata, Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete, Cement and Concrete Research 36(10) (2006) 1842-1856.
[13] M.D.A. Thomas, B. Fournier, K.J. Folliard, M.H. Shehata, et al., Performance Limits for Evaluating Supplementary Cementing Materials Using Accelerated Mortar Bar Test, ACI Materials Journal 104(2) (2007) 115-122.
[14] K. Yamada, S. Karasuda, S. Ogawa, Y. Sagawa, M. Osako, H. Hamada, M. Isneini, CPT as an evaluation method of concrete mixture for ASR expansion, Construction and Building Materials 64 (2014) 184-191.
[15] J. Lindgård, Ö. Andiç-Çakır, I. Fernandes, T.F. Rønning, M.D.A. Thomas, Alkali–silica reactions (ASR): Literature review on parameters influencing laboratory performance testing, Cement and Concrete Research 42(2) (2012) 223-243.
[16] B. Fournier, C. Rogers, C. Macdonald, Multilaboratory study of the concrete prism and accelerated mortar bar expansion tests with Spratt aggregate, 14th International Conference on Alkali Aggregate Reaction, Austin, Texas, USA, 2012, pp. 1-10.
[17] V. Sirivivatnanon, J. Mohammadi, W. South, Reliability of new Australian test methods in predicting alkali silica reaction of field concrete, Construction and Building Materials 126 (2016) 868-874.
[18] Standards Australia, AS 3582.1: Supplementary cementitious materials - Fly ash, Sydney, Australia, 2016.
[19] Standards Australia, AS 3582.2: Supplementary cementitious materials - Slag - Ground granulated blast-furnace, Sydney, Australia, 2016.
[20] Standards Australia, SA HB 79:2015 Alkali Aggregate Reaction—Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia, Standards Australia Limited, 2015.
[21] Standards Australia, AS 3972 General Purpose and Blended Cements, Sydney, Australia, 2010.
[22] ASTM International, ASTM C1778 Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete, West Conshohocken, Pennsylvania, United States, 2020.
[23] B. Fournier, R. Chevrier, A. Bilodeau, P.-C. Nkinamubanzi, N. Bouzoubaa, Comparative Field and Laboratory Investigations on the Use of Supplementary Cementing Materials (SCMs) to Control Alkali-Silica Reaction (ASR) in Concrete, in: H.d.M. Bernardes, N.P. Hasparyk (Eds.) Proceedings of the 15th International Conference on Alkali-Aggregate Reaction in Concrete, The International Conference on Alkali-Aggregate Reaction (ICAAR), Sao Paulo, Brazil, 2016.
[24] B. Fournier, J. Lindgård, B.J. Wigum, I. Borchers, Outdoor exposure site testing for preventing Alkali-Aggregate Reactivity in concrete – a review, International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2018), MATEC Web of Conferences 2018.
[25] R.D. Hooton, C. Rogers, C.A. MacDonald, T. Ramlochan, Twenty-Year Field Evaluation of Alkali-Silica Reaction Mitigation, ACI Materials Journal 110(5) (2013) 539-548.
[26] M.D.A. Thomas, A. Dunster, P. Nixon, B. Blackwell, Effect of fly ash on the expansion of concrete due to alkali-silica reaction – Exposure site studies, Cem. Concr. Compos. 33 (2011) 359–367.
[27] American Association of State Highway and Transportation Officials, AASHTO PP65 Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction, 2011.
[28] K. Kerendis, D. Hooton, Mitigating Alkali-Silica Reaction when Using High-Alkali Cements, Concr. Int. (2011) 34-39.
[29] U. Costa, T. Mangialardi, A.E. Paolini, Minimizing alkali leaching in the concrete prism expansion test at 38°C, Constr. Build. Mater. 146 (2017) 547–554.
[30] J. Lindgård, M.D.A. Thomas, E.J. Sellevold, B. Pedersen, Ö. Andiç-Çakır, H. Justnes, T.F. Rønning, Alkali–silica reaction (ASR)—performance testing: Influence of specimen pre-treatment, exposure conditions and prism size on alkali leaching and prism expansion, Cem. Concr. Res. 53 (2013) 68–90.

[31] M.J. Tapas, P. Thomas, K. Vessalas, V. Sirivivatnanon, Mechanisms of Alkali-Silica Reaction Mitigation in AMBT Conditions: Comparative Study of Traditional Supplementary Cementitious Materials, Journal of Materials in Civil Engineering 34(3) (2021) 04021460.
[32] M.J. Tapas, L. Sofia, K. Vessalas, P. Thomas, V. Sirivivatnanon, K. Scrivener, Efficacy of SCMs to mitigate ASR in systems with higher alkali contents assessed by pore solution method, Cement and Concrete Research 142 (2021) 106353.
[33] M. Thomas, The effect of supplementary cementing materials on alkali-silica reaction: A review, Cement and Concrete Research 41 (2011) 1224–1231.
[34] A. Leemann, Z. Shi, J. Lindgård, Characterization of amorphous and crystalline ASR products formed in concrete aggregates, Cement and Concrete Research 137 (2020) 106190.

Response to Reviewer Comments

Reviewer #1: Thank you for addressing my comments. However, I see that your response reflect some limitations in the study which is OK; however, you just need to make it clear to the readers. For example, the fact that the Portland cement has an alkali level of 0.60% NaOe or lower needs to be stated in the conclusion as similar studies with different cement might not show the same conclusion. Also it is important to state that different fly ashes and slags were used and if possible, state the range of alkali contents in both materials, and perhaps CaO for fly ash.

Response:

Thank you for this comment. We are grateful that you found our response to the previous comments satisfactory and we are happy to address this additional comment to further enhance the clarity of our paper.

As advised, the conclusions have been slightly modified to reflect the limitations of the study. The 0.6% Na_2O_{eq} alkali limit of the Australian cement has been added. The use of fly ashes and slags from different states in Australia have also been clearly stated as well as the fact that all SCMs used comply with Australian standards AS 3582.1 (fly ash), AS 3582.2 (slag) and SA HB 79 (Alkali-Aggregate Reaction: Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia). The range of alkali contents of the fly ashes and slags, as well as the CaO of the fly ashes have also been added. This information has also been added to Section 2 Experimental Program.

Highlights

1. Australian standards AMBT and CPT correlate well with the long-term performance of field concrete
2. CPT AS 1141.60.2 limit of 0.03% improves the correlation of AMBT, CPT and field data
3. AMBT requires a similar or more conservative dosage of SCM than the CPT
4. AS 1141.60.1 requires similar or more conservative dosage of SCM than ASTM C1567
5. AS 1141.60.1 and 60.2 can be extended for the assessment of ASR mitigation using SCMs

Credit Author Statement

Vute Sirivivatnanon: Conceptualization, Project Administration, Funding Acquisition, Methodology, Data curation, Writing- Original draft preparation, Investigation, Formal Analysis. **Paul Thomas:** Writing- Reviewing and Editing, Investigation, Formal Analysis **Marie Joshua Tapas**: Writing- Reviewing and Editing, Investigation, Formal Analysis **Thuc Nhu Nguyen:** Writing- Reviewing and Editing, Investigation, Formal Analysis.

Reliability of AMBT and CPT in testing the effectiveness of SCM to mitigate alkali-silica reaction of field concrete

Vute Sirivivatnanon[a], Paul Thomas[a], Marie Joshua Tapas[a,*] and Thuc Nhu Nguyen[a]
[a]School of Civil and Environmental Engineering, University of Technology Sydney

Abstract

This paper examines the reliability of the Australian Standard accelerated mortar bar test (AMBT) and concrete prism test (CPT), AS 1141.60.1 and 60.2, respectively, and the potential for extending these standard test methods to the determination of the type and dosage of supplementary cementitious materials (SCMs) required to mitigate deleterious alkali-silica reaction (ASR) in a similar manner to the corresponding ASTM C1567 and CSA A23.2-28A. Both AMBT and CPT have their strengths and limitations, however, their overwhelming value is in the availability of laboratory test results and their correlation with long-term performance (up to 20 years) of large concrete blocks and structural elements. Since Australia has no existing field exposure site, this paper uses reported data from CANMET's and Ontario Hydro's outdoor exposure sites in Ottawa and Kingston, respectively, in Canada and the 18-year exposure site data from the BRE site in the UK to demonstrate the efficacy of the AMBT and CPT approaches to evaluation of ASR reactivity and ASR mitigation using SCM blended cements. Good correlations are observed for moderately-reactive and highly reactive aggregates used with low-alkali cement and cement with alkali contents up to 0.9% Na_2O_{eq}. The assessment of reported research demonstrates that both AMBT and CPT have the capacity to predict the long-term performance of structural concrete. In addition, AMBT and 2-year CPT test results for eight Australian reactive aggregates are reported showing the influence of SCMs (fly ash and slag) on mitigation of expansion. Whilst both AMBT and CPT demonstrated their potential for assessing SCMs in mitigation of ASR, AMBT was found to be more conservative than CPT and higher SCM dosages were required to achieve a non-reactive classification. The accelerated test data reported coupled with the correlation of AMBT and CPT to the prediction of long term performance of concretes strongly supports the

extension of the Australian test methods AS 1141.60.1 and 60.2 for the assessment of ASR mitigation using SCMs.

Keywords: Alkali-silica reactivity, AMBT, ASR, CPT, performance limits, supplementary cementitious material

*Corresponding author: mariejoshua.tapas@uts.edu.au

1. Introduction

There are two common alkali-silica reactivity (ASR) test methods namely the accelerated mortar bar test (AMBT) and concrete prism test (CPT). The AMBT and CPT have been standardised in many national standards and used widely as listed below:

AMBT: ASTM C1260 [1], CSA A23.2-25A [2], RILEM AAR-2 [3], and AS 1141.60.1 [4]

CPT: ASTM C1293 [5], CSA A23.2-14A [6], RILEM AAR-3 [7] , and AS 1141.60.2 [8]

The AMBT and CPT have also been adopted to determine the type and dosage of supplementary cementitious materials (SCMs) required in mitigating the potential alkali-silica reaction (ASR) in concrete. The most commonly applied are the ASTM C1567 [9] and CSA A23.2-28A [10].

Thomas and Innis [11] stressed that the usefulness of various tests may be judged on the basis of (i) the ease of testing, (ii) the repeatability or precision of the outcomes, (iii) the time taken to complete the test and, ultimately, (iv) the ability of the test to predict behaviour in the field.

Both AMBT and CPT are fairly simple test methods. AMBT requires 2-3 weeks of testing while CPT requires a full year to determine the potential reactivity of an aggregate or 2 years to determine the effectiveness of a supplementary cementitious material (SCM) to mitigate ASR. The reliability of the two test methods for assessing the efficacy of SCMs in ASR mitigation or which among the two is a better test method however remain in question. CPT which in theory provides a finite supply of alkali, although widely reported as the more accurate laboratory test method [12], was found to be prone to alkali leaching leading to inconsistencies in expansion results [13-15]. Since ASR expansion is influenced by the amount of alkalis present in the pore solution, leaching of alkalis over time can lead to variability in expansion results, underestimation of expansion and even to the determination of much lower dosages of SCMs required for effective mitigation if leached alkalis cannot be accounted for [12-15]. AMBT, on the other hand, although was found by Fournier et al. [16] to have better precision than the CPT is heavily criticized due to the infinite supply of alkali and the use of high testing temperature (1M NaOH at 80 °C) [12]. Since both test methods remain controversial and there are conflicting results reported in literature, undoubtedly the most challenging requirement is their accuracy to predict the effectiveness of SCM in mitigating ASR of field concrete. This can only be assessed from well-kept record of test results and long-term evaluation of real structures or field-exposed large concrete blocks and structural elements.

1.1 Reliability of AMBT and CPT in evaluating the reactivity of aggregate consistent with field performance

The Australian AMBT AS 1141.60.1 and CPT AS 1141.60.2 adopted test procedures correspondingly from ASTM 1260 and ASTM C1293 with different performance limits leading to a new class of slowly reactive aggregates in the case of AMBT AS1141.60.1. The expansion limits for AMBT are listed in Table 1. For the CPT, AS 1141.60.2 specifies an expansion limit of 0.03% compared to the 0.04% used in the corresponding ASTM C1293 and CSA 23.2-14A test method.

Table 1 Comparison of ASTM and AS accelerated mortar bar expansion limits

ASTM C1260		AS 1141.60.1		
Interpretation	14 days	Classification	10 days	21 days
Innocuous	< 0.10%	Non-reactive	-	< 0.10%*
Uncertain	0.10 to 0.20%	Slowly reactive	< 0.10%*	≥0.10%* and < 0.30%
Potential deleterious	≥ 0.2*%	Reactive	≥ 0.10%* or	≥ 0.30%

* For naturally occurring fine aggregates the limit is 0.15%

The reliability of Australian AMBT and CPT test methods in predicting ASR of field concrete has been compiled and examined by Sirivivatnanon et al. [17]. It was found from the international and Australian research data that AMBT was an excellent screening test for non-reactive aggregates and to correctly classify 'reactive' aggregates consistent with field performance with few exceptions. The concrete prism test was found to be more reliable as it correctly classified almost all 64 aggregates against known field performance.

In this paper, the extension of the Australian AMBT and CPT method to determine the effectiveness of SCM in mitigating ASR expansion, similar to the ASTM C1567 and CSA A23.2-28A, respectively, is examined. In particular, the reliability of these laboratory test methods in determining the dosage of SCM for ASR mitigation consistent with reported field concrete performance is examined from a collection of long-term (18-20 years) exposure concrete specimens at CANMET Ottawa (Canada), Ontario Hydro & MTO Kingston (Canada) and BRE Watford exposure site (UK).

2. Experimental Program

A total of 8 aggregates were tested to both the Australian AMBT AS 1141.60.1 and CPT AS 1141.60.2. Two types of supplementary cementitious materials (SCMs): fly ash and slag; were used. The fly ashes and slags, provided by suppliers from various states/regions in Australia, comply with

AS 3582.1 (Supplementary Cementitious Materials Part 1: Fly Ash) [18] and AS 3582.2 (Supplementary Cementitious Materials Part 1: Slag-Ground granulated blast furnace) [19], respectively. AS 3582.1 requires fly ash to have SiO_2+Al_2O_3+Fe_2O_3≥70% while AS 3582.2 specifies maximum 15% MgO and 18% Al_2O_3 in the slag. Moreover, as recommended by SA HB 79 "Alkali-Aggregate Reaction-Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia" [20], fly ashes and slags used in this testing program have total alkali content ≤3% Na_2O_{eq} and ≤1% Na_2O_{eq} respectively. All fly ashes have CaO ≤8%. A number of Type GP cements complying with AS 3972 (General Purpose and Blended Cements) [21], were also used. All cements used for the AMBT and CPT testing program have an alkali content ≤0.6% Na_2O_{eq}. The source of GP cement and SCMs was chosen according to their availability in the location of individual aggregate. Thus, the outcomes of these tests are highly relevant to the usage of the aggregates.

Testing was conducted in three commercial laboratories in Australia. The AMBT and CPT tests per set of aggregates and SCMs were only carried out once (i.e. by a single laboratory and therefore the testing program was not similar to a proficiency test). The results reported in this manuscript are therefore combined results from the three participating laboratories. This was agreed as the most practical approach since the AMBT and CPT tests were carried out as part of a commercial program participated by the aggregate and SCM suppliers in Australia under the leadership of Cement Concrete and Aggregates Australia (CCAA). The choice of which aggregates and SCMs to test depends on their availability in the Australian region and therefore means that if fly ash for instance is more abundant in the region, then it is the SCM that was tested in the program.

2.1 Extension of Australian Test Methods for Mitigation

AS 1141.60.1 test procedure is similar to ASTM C1260 and was used to test the effectiveness of various SCMs in mitigating ASR similar to ASTM C1567. Comparison will be made in the use of the respective criteria in AS 1141.60.1 (see Table 1) and ASTM C1567 to gauge the efficacy of SCM. ASTM C1567 specifies that expansion of less than 0.10 % at 14 days AMBT bath exposure indicates a low risk of deleterious expansion when used in concrete under field conditions while expansion of more than 0.10 % at 14 days is indicative of potentially deleterious expansion.

AS 1141.60.2 test procedures, which are similar to ASTM C1293 and Canadian Standard CSA A23.2-14A, were used to determine the length change of concrete due to ASR with an extended testing period from one year to two years for combinations of cementitious materials for mitigation determination. Comparison will be made in the use of the respective criterion in AS 1141.60.2, ASTM C1293 or CSA A23.2-28A in gauging the efficacy of the SCM.

3. Experimental Results

3.1 Alkali-Silica Reactivity by AMBT and CPT

The 10, 14 and 21-day AMBT expansion results and 1-year CPT expansion results of all 8 aggregates are tabulated in Table 2. It is worth noting that whereas the tests were conducted in accordance with AS standards, ASTM C1778 (Table 4) was used to classify the aggregate reactivity of the CPT test results. This is just to provide a wider range of reactivity classification as opposed to just reactive (≥0.03%) and non-reactive classification (<0.03%) in AS AS1141.60.2. Highly reactive aggregates notably require higher SCM dosage for effective mitigation than moderately reactive aggregates as shown in Table 3.

Results in Table 2 show that similar rock type from different quarries, such as the two meta greywacke aggregates can exhibit very different susceptibility to alkali-silica reactivity (ASR) determined from the expansion tests. Moreover, the degree of reactivity of each aggregate, determined from AMBT, may differ from that determined from the CPT. In Table 2, it can be seen that a basalt and a quartz are found to be reactive by the AMBT but non-reactive by the CPT. CPT results have been found to be more reliable and consistent with long-term field performance [17].

Table 2 AMBT and CPT Expansion Results for Aggregate Reactivity

	Aggregate	AS1141.60.1 AMBT				AS1141.60.2 CPT	
		10-day	14-day	21-day	AS1141.60.1 Classification	1-year	ASTM C1778 Classification
1	Dacite	0.35	0.47	0.64	Reactive	0.233	Highly R
2	Rhyolite	0.24	0.35	0.47	Reactive	0.142	Highly R
3	Meta Greywacke	0.23	0.34	0.49	Reactive	0.158	Highly R
4	Quartz	0.09	0.15	0.27	Slowly-R	0.003	Non-R
5	Hornfels	0.17	0.27	0.40	Reactive	0.070	Moderate R
6	Rhyodacite	0.23	0.32	0.43	Reactive	0.059	Moderate R
7	Meta Greywacke	0.23	0.30	0.39	Reactive	0.053	Moderate R
8	Basalt	0.52	0.73	1.05	Reactive	0.007	Non-R

3.2 Type and dosage of SCM required to mitigate ASR

Table 3 shows the summary of AMBT and CPT results for ASR mitigation. Testing of the effectiveness of SCM to mitigate ASR commenced following the availability of AMBT results for aggregate reactivity and prior to the completion of CPT. Thus, basalt and quartz aggregates which are both reactive in AMBT but not in CPT were still tested with various dosages of fly ash using both test methods. From Table 3, it was found that both fly ash and slag are effective in mitigating ASR with a range of 15-25% fly ash and 30-50% slag required to mitigate ASR depending on the aggregate and its reactivity. Further, it is notable that higher dosages of fly ash are required to mitigate ASR for ASTM C1778 [22] highly reactive (HR) aggregates than moderately reactive (MR) aggregates.

The reliability of these short-term laboratory tests in predicting long-term field performance will be evaluated and discussed in Section 4. It should be noted that the AMBT always gives similar or more conservative SCM dosages for mitigation than the CPT. Amongst the two AMBT methods, AS 1141.60.1 requires similar or more conservative SCM dosage than ASTM C1567.

As outlined in the metholodogy, since the expansion results from the AMBT and CPT tests reported in Tables 2 and 3 are combined results from the three participating laboratories with one aggregate+SCM combination tested only by a single laboratory (i.e. testing was not carried out similar to a proficieny test), the spread of data is not possible to report. This was agreed as the most practical approach since the AMBT and CPT tests were carried out as part of a commercial program participated by various aggregate and SCM suppliers in Australia. The choice of which aggregate and SCM combination to test depends on their availability in the Australian region.

Table 3 Summary of AMBT and CPT expansion results for ASR Mitigation

Aggregate	Type	%	AMBT Expansion (%)			Classification		CPT Expansion (%)		Classification	
			10 d	14d	21 d	ASTM C1567	AS1141 60.1	1 Y	2 Y	CSA A23.2-28A	AS1141 60.2
Dacite	Eraring Flyash	0.0	0.35	0.47	0.64	R	R	0.233	-	R	R
		10.0	0.11	0.18	0.29	R	R	0.080	0.148	R	R
		15.0	0.03	0.06	0.11	N	SR	0.008	0.022	N	N
		25.0	0.01	0.01	0.02	N	N	-0.002	0.001	N	N
Rhyolite	Eraring Flyash	0.0	0.24	0.35	0.47	R	R	0.142	-	R	R
		10.0	0.04	0.07	0.12	N	SR	0.001	0.005	N	N
		15.0	0.02	0.03	0.04	N	N	-0.005	-0.003	N	N
		25.0	0.01	0.01	0.02	N	N	-0.006	0.001	N	N
Meta Greywacke	Central Qld Flyash	0.0	0.23	0.34	0.49	R	R	0.158	-	R	R
		10.0	0.10	0.19	0.30	R	R	0.058	0.115	R	R
		15.0	0.04	0.08	0.15	N	SR	0.021	0.046	R	R
		25.0	0.01	0.02	0.04	N	N	0.005	0.011	N	N
Quartz	Central Qld Flyash	0.0	0.09	0.15	0.27	R	R	0.003	-	N	N
		10.0	0.03	0.06	0.13	N	SR	-0.003	0.007	N	N
		15.0	0.01	0.03	0.05	N	N	-0.004	-0.003	N	N
		25.0	0.00	0.01	0.01	N	N	-0.008	-0.007	N	N
Hornfels	ICL Slag	0	0.17	0.27	0.40	R	R	0.070	0.155	R	R
		30.0	0.10	0.17	0.27	R	R	-0.006	0.013	N	N
		40.0	0.04	0.07	0.13	N	SR	-0.023	-0.011	N	N
		50.0	0.02	0.03	0.04	N	N	-0.011	-0.003	N	N
Rhyodacite	Mt Piper Flyash	0.0	0.23	0.32	0.43	R	R	0.059	0.087	R	R
		15.0	0.06	0.09	0.15	N	SR	0.002	0.010	N	N
		22.5	0.02	0.03	0.04	N	N	-0.006	-0.003	N	N
		30.0	0.02	0.02	0.02	N	N	-0.006	-0.001	N	N
Meta Greywacke	Sunstate Flyash	0	0.23	0.30	0.39	R	R	0.053	0.122	R	R
		15.0	0.03	0.04	0.07	N	N	-0.017	-0.009	N	N
		20.0	0.02	0.03	0.03	N	N	-0.006	-0.001	N	N
		25.0	0.01	0.02	0.02	N	N	-0.007	-0.009	N	N
Basalt	Eraring Flyash	0	0.52	0.73	1.05	R	R	0.007	0.024	N	N
		15.0	0.05	0.08	0.21	N	SR	-0.009	-0.007	N	N
		22.5	0.02	0.02	0.05	N	N	-0.010	-0.005	N	N
		30.0	0.01	0.02	0.02	N	N	-0.014	-0.009	N	N

AS1141.60.1 & 60.2 Classification: N - non reactive, SR – slowly reactive, R – reactive.
ASTM C1567 & CSA A23.2-28A Classification: N – non reactive, R – reactive.

4. Reliability of AMBT and CPT in predicting ASR mitigation of field concrete

In this paper, the extension of AMBT and CPT methods to determine the effectiveness of SCMs in mitigating ASR expansion, such as the ASTM C1567 and CSA A23.2-28A respectively will be examined. In particular, the reliability of these laboratory test methods in determining the dosage of SCM for ASR mitigation consistent with field concrete will be determined from inspection of published long-term (18-20 years) exposure concrete test data at CANMET Ottawa Canada, Ontario Hydro & MTO Kingston Canada and BRE Watford UK exposure site [23-26]. Data from other exposure sites are not considered as they are usually short-term exposure.

4.1 Correlation between short-term laboratory and field exposure

The extent of alkali-silica reaction in concrete depends largely on the reactivity of aggregate, the level of alkali and the environmental conditions such as the temperature and relative humidity. The reactivity of aggregate has been classified from petrographic examination and the expansion from the standard AMBT and CPT. ASTM C1778 [22] or AASHTO PP65 [27] classification of aggregate reactivity is reproduced in Table 4. ASTM C1778 or AASHTO PP65 are not test methods but rather guide for reducing the risk of deleterious alkali-aggregate reaction in concrete. Based on the expansion results obtained from test methods ASTM C1260 and ASTM C1293, ASTM C1778 classifies aggregate reactivity into four "aggregate reactivity classes". Based on the reactivity classification, the risk levels are assessed and required levels of prevention are identified.

The alkali in concrete is largely derived from the Portland cement and reference is made to low-alkali (LA) cement and high-alkali (HA) cement. In this paper, LA cement and HA cement are defined in terms of their sodium oxide equivalent (Na_2O_{eq}) of no greater than 0.6% and greater than 0.8% respectively.

Table 4 ASTM C1778 & AASHTO PP65 classification of aggregate reactivity

Aggregate-Reactivity Class	Description of Aggregate Reactivity	1-Year Expansion in Test Method ASTM C1293, %	14-Day Expansion in Test Method ASTM C1260, %
R0	Non-reactive	<0.04	<0.10
R1	Moderately reactive	≥0.04, <0.12	≥0.10, <0.30
R2	Highly reactive	≥0.12, <0.24	≥0.30, <0.45
R3	Very highly reactive	≥0.24	≥0.45

A range of concretes manufactured from moderately and highly reactive aggregates with both LA and HA cement has been tested in the laboratory as well as large concrete blocks or structural elements in the field [23-26]. In most cases, the performance of the field-exposed concrete has been reported in terms of expansion and cracking. Expansion within 0.05% is associated with non-deleterious deterioration. The results of laboratory tests and their correlation with long-term performance (up to 20 years) of large concrete blocks and structural elements at CANMET's and Ontario Hydro's outdoor exposure sites in Ottawa and Kingston in Canada, and the 18-year exposure site data from the BRE site in the UK are examined.

4.2 CANMET outdoor exposure site

Fournier et al. [23] showed that low-alkali cement can be used to limit the deleterious expansion of concrete blocks up to 15-year exposure at CANMET outdoor exposure site in Ottawa, Canada. These blocks were manufactured from 4 different moderately-reactive aggregates, one highly-reactive and one very extremely-reactive aggregate. There is a good correlation of short-term laboratory tests to long-term 15-year field performance of concrete manufactured from high-alkali 0.9% Na_2O_{eq} cement and 20% fly ash for four moderately-reactive aggregates. There was one exception with a Canadian argillaceous limestone which showed deleterious expansion even with 10% SF. All concretes made from three Australian aggregates and low-alkali cement without SCM showed non-deleterious expansion in the field exposed blocks (Table 5). Fournier et al. reported some discrepancies in the outcomes of CPT (with high-alkali cement) and large concrete blocks results where freeze and thaw conditions existed as in the case of CANMET exposure site.

Fournier et al. [24] provided laboratory AMBT and CPT results and corresponding long-term 20-year field performance of concrete blocks manufactured mainly from high-alkali cement (0.9% Na_2O_{eq}) and SCM (fly ash, slag and silica fume) with one moderately reactive Sudbury gravel (Su) and one highly reactive Spratt limestone aggregate (Sp). The blocks were exposed at CANMET outdoor exposure site in Ottawa, Canada. Block expansion above 0.05% was deemed to be deleterious expansion. The results are compiled in Table 6. In addition to the concrete blocks with the inherent alkali from the cement, companion concrete blocks containing added alkali were also exposed to see the effect of higher alkali and SCM on long-term performance. The expansion results of the concrete blocks boosted with alkali are not reported in this paper since they are not relevant to Australian context. Australian cement has a low alkali limit of 0.6%Na_2O_{eq} and therefore field expansion results of blocks made with up to 0.9% Na_2O_{eq} alkali cement are already sufficient to address the objectives of the work.

Table 5 Correlation of short-term laboratory tests to long-term 15-year field performance at CANMET outdoor exposure site in Ottawa, Canada (concretes with inherent alkali from cement) [23]

Detail of aggregates	Agg	AMBT	CPT		SCM	Cement	Block expansion ≤0.05% @15year
		14 days	1 year	2 year			
Moderately reactive aggregates							
Gr Granite and granitic gneiss, Canada	Gr	NA	NA	-	0	Low-alkali	√
Rg Granitic gravel, Australia	Rg	NA	NA	-	0	Low-alkali	√
Al Sandstone, greywacke, mudstone, volcanic gravel, Canada	Al	0.36	0.09	-	0	Low-alkali	√
Lm Argillaceous limestone, Canada	Lm	NA	NA	-	0	Low-alkali	No
Su Sandstone, quartzwacke, arkose, greywacke and argillite, Canada	Su	0.278	0.075	-	0	Low-alkali	√
Su Sandstone, quartzwacke, arkose, greywacke and argillite, Canada	Su	0.048	-	0.003	20%FA	0.9% Na_2O_{eq}	√
Al Sandstone, greywacke, mudstone, volcanic gravel, Canada	Al	0.037	-	0.007	20%FA	0.9% Na_2O_{eq}	√
Ed Sandstone, claystone, chart gravel, Canada	Ed	0.023	-	0.022	20%FA	0.9% Na_2O_{eq}	√
Gr+ Granite and granitic gneiss, Canada	Gr+	NA	-	NA	20%FA	0.9% Na_2O_{eq}	√
Lm Argillaceous limestone, Canada	Lm	NA	-	NA	10%SF	0.9% Na_2O_{eq}	No
Highly reactive and Extremely reactive aggregates							
Ql Greywacke, Australia	Ql	NA	NA	-	0	Low-alkali	√
Re Mixed volcanic, Australia	Re	NA	NA	-	0	Low-alkali	√

NA = not available, S = ggbfs; FA = fly ash (ASTM Class F), SF = silica fume, √ = block expansion ≤0.05%.

Table 6 Laboratory AMBT and CPT expansion compared to the status of large concrete blocks after 20-year exposure at CANMET Ottawa outdoor exposure site [24]

Aggregate	AMBT	CPT		SCM	Alkali in Cement % Na_2O_{eq}	Na_2O_{eq} Kg/m^3	Block expansion ≤0.05% @20year	Field consistent with lab tests
	14 days	1 year	2 year					
Su	0.278	0.157	-	0	0.4% Na_2O_{eq}	1.68	√	No
Su	0.278	0.157	-	0	0.9% Na_2O_{eq}	3.78	No	Yes
Su	0.140	-	0.034*	35%S	0.9% Na_2O_{eq}	2.46	No	Yes*
Su	0.043	-	0.014	50%S	0.9% Na_2O_{eq}	1.89	√	Yes
Su	0.048	-	0.008	20%FA	0.9% Na_2O_{eq}	3.02	√	Yes
Su	0.021	-	0.007-	30%FA	0.9% Na_2O_{eq}	2.65	√	Yes
Su	0.112	-	0.030*	7.5%SF	0.9% Na_2O_{eq}	3.50	No	Yes*
Su	0.078	-	0.023	10.0%SF	0.9% Na_2O_{eq}	3.40	No	No
Su	0.052	-	0.009	12.5%SF	0.9% Na_2O_{eq}	3.31	√	Yes
Sp	0.391	0.207	-	0	0.4% Na_2O_{eq}	1.68	No	Yes
Sp	0.391	0.207	-	0	0.9% Na_2O_{eq}	3.78	No	Yes
Sp	0.190	-	NA	35%S	0.9% Na_2O_{eq}	2.46	No	Yes, AMBT
Sp	0.066	-	0.014	50%S	0.9% Na_2O_{eq}	1.89	√	Yes
Sp	0.103	-	NA	20%FA	0.9% Na_2O_{eq}	3.02	No	Yes, AMBT
Sp	0.032	-	0.005	30%FA	0.9% Na_2O_{eq}	2.65	√	Yes
Sp	0.180	-	NA	7.5%SF	0.9% Na_2O_{eq}	3.50	No	Yes, AMBT
Sp	0.142	-	0.038*	10%SF	0.9% Na_2O_{eq}	3.40	No	Yes*

*designates the use of Australian CPT expansion limit of 0.03% rather than 0.04% limit in CSA 23.2-28A.

S = ggbfs; FA = fly ash (ASTM Class F), SF = silica fume, NA = not available, √ = block expansion ≤0.05%.

With both the moderately-reactive Sudbury gravel and highly-reactive Spratt limestone aggregate with high-alkali 0.9% Na_2O_{eq}, there is an outstanding consistency between AMBT, CPT and the large concrete blocks with no added alkali especially if the Australian CPT limit of 0.03% was used for expansion at one year (without SCM) and two years (with SCM) instead of the 0.04% expansion limit used in ASTM C1293 or CSA 23.2-28A. When both AMBT and CPT showed effective mitigation from an SCM, the corresponding concrete blocks showed no deleterious expansion greater than 0.05% after 20-year exposure. On the other hand, when both AMBT and CPT showed an amount of SCM to be ineffective in mitigating the alkali-silica reaction in one or both laboratory tests, the corresponding concrete blocks showed deleterious expansion greater than 0.05%. Interestingly for concrete with SCM, even with no CPT results available, AMBT has shown to be a consistent indicator of field performance as shown in the Spratt limestone concrete with 7.5%SF, 20%FA and 35%S mixes.

There is one exception to this general finding for Sudbury gravel where both AMBT and CPT showed 10% silica fume to be effective in mitigating the alkali-silica reaction whereas the large concrete block displayed deleterious expansion after 20 years field exposure. This mix has high alkali at 3.4 kg/m^3 of Na_2O_{eq}. It should also be noted that the low alkali (0.4% Na_2O_{eq}) cement without any SCM is proven effective in preventing deleterious expansion of the large concrete blocks with the moderately-reactive Sudbury gravel, but is ineffective for the highly-reactive Spratt limestone.

The results from Fournier et al. [24] field exposure would suggest excellent correlation between laboratory tests and 20-year field performance when cement with alkali content up to 0.9% Na_2O_{eq} is used. Australian cement has a maximum allowable alkali content of 0.6% Na_2O_{eq} so the data examined provide significant information for current Australian practice.

Kerenidis & Hooton [28] studied the mitigation of ASR in high-alkali cement concretes with SCM. They experimented with three cements with inherent alkali contents of 0.97%, 1.08% and 1.13% Na_2O_{eq} using either fly ash or slag. The cement alkali content was adjusted to 1.25% Na_2O_{eq} as per CPT standard. Results of the study shown in Figure 1 demonstrate that all the fly ash or slag cement replacement levels, selected from CSA A23.2-27A, were effective in controlling deleterious expansions for both Spratt (highly reactive) and Sudbury (moderately reactive) aggregates when tested according to CSA A23.2-28A. From the results, they suggested that it appeared unnecessary to increase the cement alkali content above 1.25% Na_2O_{eq} for testing. It should be noted that while the inherent alkali content in the cement does not affect the outcomes based on the expansion criterion of 0.04%, it can significantly influence the magnitude of CPT expansion in concrete mixes without SCM. The effect is less significant in mixes with SCM. In the same study, Kerenidis & Hooton [28] also compared the AMBT and CPT results to confirm that AMBT results are more conservative than the CPT results in terms of the required mitigation dosage of fly ash or slag consistent with the observation in Table 3.

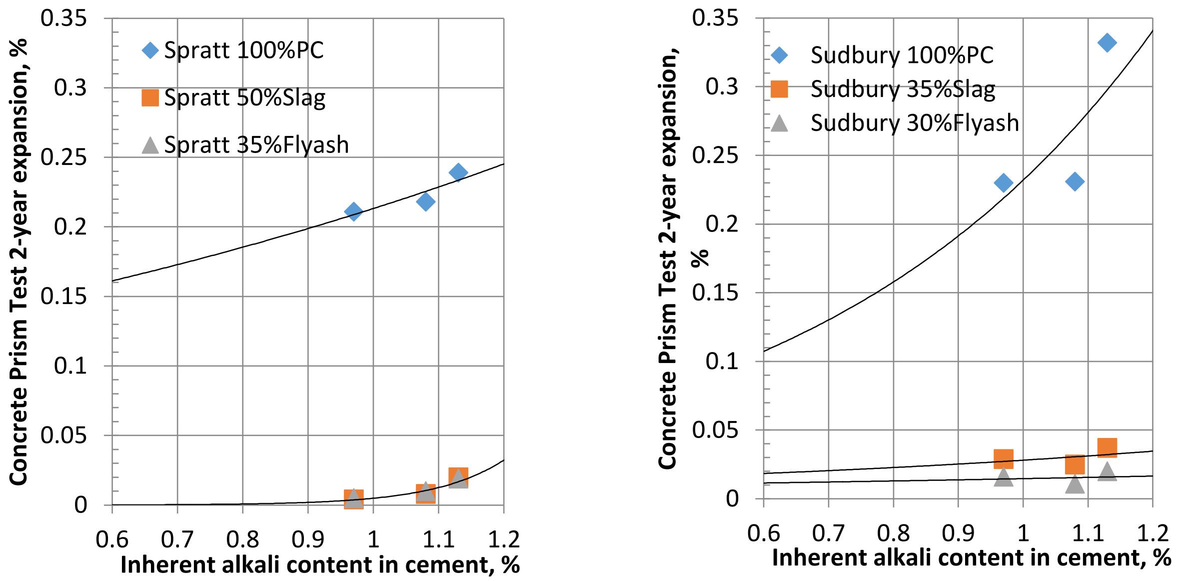

Fig. 1. Effect of cements' inherent alkali content on 2-year expansion of concrete with the same 1.25% Na_2O_{eq} in CPT [28]

4.3 MTO Kingston exposure site

Hooton et al. [25] demonstrated a correlation between short-term laboratory AMBT tests to long-term 20-year field performance of concrete beams and slabs manufactured from a high-alkali cement with and without a range of SCMs and a highly reactive Spratt limestone. This correlation can be extended to their CPT results if the Australian CPT limit of 0.03% was used (Table 7). Two mixes pass both AMBT & CPT tests to show non-deleterious expansion and show less than 0.05% expansion in the field specimens after 20 years exposure. Two other mixes fail both AMBT & CPT (Australian CPT limit of 0.03%) and show deleterious expansion (>0.05%) in the field specimens. In the case of mixes without SCM, the reactive aggregate showed AMBT 14-day expansion greater than 0.1% for mixes with low-alkali and high-alkali cement, consistent with field exposed concrete beams and slab expanding greater than 0.05% after 20-year exposure at MTO Kingston exposure site.

Table 7 Laboratory AMBT and CPT expansion compared to the status of unreinforced and reinforced concrete beams and slabs after 20-year exposure at an outdoor exposure site in Kingston [25]

Mix	AMBT	CPT		SCM	Cement %Na_2O_{eq}	Na_2O_{eq} kg/m^3	UR beam ≤0.05% @20year	R beam ≤0.05% @20year	Slab ≤0.05% @20year	Field consistent with lab tests
	14 days	1 year	2 year							
1	0.059	<<0.03	<0.03	50%S	0.79%	1.65	<0.05	<0.05	<0.05	Yes
2	0.111	<0.03	0.037	18%FA	0.79%	2.72	>0.05	>0.05	>0.05	Yes*
3	0.187	<0.03	0.045	25%S	0.79%	2.48	>0.05	>0.05	>0.05	Yes*
4	0.041	<<0.03	<0.03	25%S, 3.8%SF	0.79%	2.36	<0.05	<0.05	<0.05	Yes
5	0.435	<0.03	0.04	0	0.48%	2.00	>0.05	>0.05	>0.05	Yes AMBT
6	0.315	0.13	0.15	0	0.79%	3.30	>0.05	>0.05	>0.05	Yes

*designates the use of Australian CPT expansion limit of 0.03% rather than 0.04% limit in CSA 23.2-28A.
S = ggbfs; FA = fly ash (ASTM Class F), SF = silica fume, UR = unreinforced, R = reinforced.
CPT expansions are read off from Fig. 2 in Hooton et al. (2013) [25]

Hooton et al. [25] concluded that when high-alkali cement was replaced with 50% slag or 25% slag + 3.8% silica fume interground with a high-alkali Portland cement, there was no sign of ASR or cracking after 20 years exposure. The findings in Table 7 demonstrated the consistency between the expansion of field concretes with the laboratory AMBT and CPT results provided that the Australian CPT expansion limit of 0.03% at 2 years for concrete with SCM was used.

4.4 BRE outdoor exposure site near Watford, UK

Thomas et al. [26] examined the effectiveness of two sources of fly ash in mitigating deleterious expansion of two sizes of large concrete blocks for up to 18 years exposure at BRE outdoor exposure site near Watford, UK. Three reactive flint sands and one highly reactive greywacke coarse and fine aggregates were tested with a high-alkali (1.15% Na_2O_{eq}) cement. Concrete with a range of binder contents, as controls and with 25% and 40% fly ash, were tested in both AMBT and non-standard CPT. Results with one fine fly ash (FF, 3.4%LOI, 8.0% >45 µm) are compiled in Table 8. Thomas et al. [26] concluded that the results clearly showed the effectiveness of fine fly ash in controlling the expansion of the concrete blocks consistent with the available AMBT and non-standard concrete prisms with no boosted alkali and cured at 38°C (no expansion results reported). There were exceptions with two flint-bearing mixes made with a relatively coarse FA and high alkali contents.

Table 8 BRE outdoor exposure site study of the effectiveness of fly ash in ASR mitigation in concrete blocks and cubes after 18-year exposure [26]

Aggregate	AMBT 14-day	SCM	Binder content	Na_2O_{eq} kg/m^3	Block expansion ≤0.05% @18year	Field consistent with lab tests	Note
TV, BT, PB	-	0%FF	550	6.33	No	-	No lab test results
	-	25%FF	550	4.74	√	-	No lab test results
	-	40%FF	550	3.80	√	-	No lab test results
TV, BT, PB	-	0%FF	475	5.46	No	-	No lab test results
	-	25%FF	475	4.09	√	-	No lab test results
	-	40%FF	475	3.28	√	-	No lab test results
TV, BT	0.34-0.40	0%FF	412	4.74	No	Yes	
	0.06-0.08	25%FF	400	3.45	√	Yes	
	0.02	40%FF	400	2.76	√	Yes	
GW	-	0%FF	450	5.18	No*	-	Extensive cracking width up to 5mm
	-	25%FF	450	3.88	√*	-	No cracking
	-	0%FF	350	4.03	No*	-	Light cracking width up to 1mm
	-	25%FF	360	3.11	√*	-	No cracking

TV: Thames Valley river sand 50% flint, BT: Crushed sand 55% flint and quartz, PB: Sea-dredge sand similar composition to TV, GW: Grey-wacke highly reactive coarse & fine, FF: Fly ash 3.4%LOI 8.0% >45 µm.

Thomas and Innis (1999) [11] published data from 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 CPT and the 14-day expansion in AMBT. 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 0.04% limit at 2 years in the CPT.

5. Discussion

In this study, reported data from CANMET's and Ontario Hydro's outdoor exposure sites in Canada and the 18-year exposure site data from the BRE site in the UK were examined against laboratory results to investigate the efficacy of the AMBT and CPT approaches to evaluate aggregate reactivity and ASR mitigation using SCM blended cements. The results of this study demonstrate that there is a strong correlation between AMBT, CPT and field exposure data up to an exposure period of 20 years, particularly, when CPT AS 1141.60.2 limit of 0.03% is used. It is notable that the AS CPT limit is more conservative than the ASTM C1293/CSA 23.2-28A limit of 0.04% at 2 years which has proven useful in correctly classifying ASR potential consistent with field performance. Australian AMBT AS 1141.60.1 is also notably more conservative than ASTM C1567 as it has a 21-day expansion limit of 0.10% to be deemed non-reactive in comparison to ASTM's 0.10% expansion limit at 14 days. Since ASTM C1567 showed very good correlation to field performance (Tables 5-8), this suggests that AS 1141.60.1 will also perform to similar capacity. This is further supported by data in Table 3 which show that amongst the two AMBT methods, AS 1141.60.1 requires similar or more conservative SCM dosage than ASTM C1567. Based on the results of this study, Australian standards for assessing aggregate reactivity, AS 1141.60.1 and AS 1141.60.2, have the potential to be extended for use in assessing the efficacy of SCMs in ASR mitigation.

Several researchers have argued against the reliability of the AMBT and CPT tests because of their reported limitations [12]. In the case of CPT, leaching is the biggest concern and although several studies have focused on reducing the leaching in CPT, the issue remains unresolved [29, 30]. Whereas, the focus of recent studies is on perfecting the test methods, it should be noted that these tests were developed to assess aggregate reactivity and SCM efficacy in very specific conditions and the limits were established based on correlation/benchmarking with field exposure data. This means that in the case of CPT for example, if the test is carried out precisely according to the standard in the manner that the standard is benchmarked, then the leaching of alkalis is accounted for. However, as the test is empirical (i.e. by correlation or benchmarking), any change to the method makes the limits invalid and new limits will need to be defined by a thorough benchmarking program. Alternatively, the test limits can also be changed to accommodate existing field data similar to the Australian CPT limit (i.e. AS expansion limit of 0.03% is adopted rather than 0.04% so that the CPT test correlates with field exposure tests). This is an adjustment of the threshold based on an empirical observation by correlation with published long-term field performance data.

Another important outcome of this study is the expansion results of the 8 Australian aggregates in Table 3 showing that AMBT provides either similar or more conservative dosage than CPT when used to determine the dosage of SCM required to mitigate ASR and even a more accurate indicator of field performance than CPT as shown in Table 6. Moreover, Tables 6 and 8 also show that AMBT is as accurate when it is the only standard laboratory test available. This is likely because whereas CPT in theory contains a fixed amount of alkali, the available alkali in the pore solution is reduced over time due to leaching [12, 13], hydration reactions (i.e. binding of the alkalis in the hydration products especially when SCMs are incorporated in the binder) [31-33], and formation of ASR products [32, 34]. AMBT on the other hand, provides excessive 1M NaOH alkali supply to sustain ASR and replenish the alkalis consumed in the mortar. The continuous supply of alkali in the mortar makes AMBT a more conservative test method for assessing the required SCM dosage for ASR mitigation. This however also implies how critical the proper identification of expansion limits are by benchmarking to ensure that SCM dosages determined from the test are not overly conservative. A study of ASTM C1567 has reported that extending the duration of the test to 28 days as oppose to the 14-day limit is overly conservative and results in estimates of much higher levels of SCM (by 1.5 times on average) to control expansion than that actually required in the field [13].

The review of the correlation of these laboratory tests and long-term field performance data fully support the adoption of these Australian standards and corresponding expansion limits to determine the type and dosage of SCM required to mitigate ASR in the long term. Based from evaluated data, these findings are applicable to cement with alkali contents up to 0.90% Na_2O_{eq}. Australian cement currently has maximum allowable alkali content of 0.60% Na_2O_{eq} and therefore these results provide valuable information for current Australian practice.

6. Conclusions on the reliability of AMBT and CPT in predicting field performance

This paper examined the possible extension of the Australian AMBT and CPT to determine the effectiveness of SCMs in mitigating ASR expansion. Extensive laboratory accelerated tests (AMBT and CPT) were carried out in Australia and assessed with respect to the compilation of the correlation between laboratory accelerated tests and long-term performance (≥15 years) of field exposed large concrete blocks or structural elements at CANMET Ottawa Canada, Ontario Hydro & MTO Kingston Canada and BRE Watford UK exposure. All AMBT and CPT tests carried out in Australia made use of cement with alkali content ≤0.60% Na_2O_{eq} and SCMs complying with Australian standards AS 3582.1 (fly ash) and AS 3582.2 (slag). Fly ashes and slags were sourced from various parts of Australia and have total alkali content ≤3% Na_2O_{eq} and ≤1% Na_2O_{eq} respectively as recommended by SA HB 79 “Alkali-Aggregate Reaction-Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia”. All fly ashes contain ≤8% CaO. The conclusions of the study are outlined below.

1. Australian standards AMBT and CPT correlate well with the long-term performance of field concrete with SCM up to an exposure period of 20 years for concrete made with cement with alkali content of up to 0.90% Na_2O_{eq}. This is particularly the case when the Australian CPT expansion limit of 0.03% at 2 years is used instead of the 0.04% expansion limit used in the ASTM and Canadian standards. Australian cement has a maximum allowable alkali content of 0.60% Na_2O_{eq} and therefore, these findings are applicable and valuable to the mitigation of ASR in Australia.
2. AMBT has proven to be a more accurate indicator of field performance than CPT if there were conflicting results between the two laboratory tests as shown in Table 6. AMBT is as accurate when it is the only standard laboratory test available such as in the case of concrete tested at the BRE and CANMET Ottawa outdoor exposure sites (Tables 6 and 8).
3. In determining the effectiveness of SCMs (fly ash and slag) in mitigating ASR, the AMBT requires a similar or more conservative dosage of SCM than the CPT. Amongst the 2 AMBTs, AS 1141.60.1 has been found to require a similar or more conservative dosage of SCM than ASTM C1567.
4. These findings support the extension of both Australian test methods AS 1141.60.1 (AMBT) and AS 1141.60.2 (CPT) for mitigation based on the existing expansion criteria but with an extended period of 2 years for the CPT.

The data examined in this study, to the authors' best knowledge, are the only available long-term data (≥15 years) existing in literature. It is also worth noting that Australia has no existing field exposure site and hence, this study made use of field exposure data from other parts of the world to demonstrate the efficacy of the Australian AMBT and CPT approaches to the evaluation of ASR mitigation using SCM blended cements.

Acknowledgement

This study is funded through the Australian Research Council Research Hub for Nanoscience-Based Construction Materials Manufacturing (NANOCOMM) with the support of Cement Concrete and Aggregates Australia (CCAA).

References

[1] ASTM International, ASTM C1260 Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), West Conshohocken, Pennsylvania, United States, 2014.
[2] Canadian Standards Association, CSA A23.2-25A Test method for detection of alkali-silica reactive aggregate by accelerated expansion of mortar bars, Ontario, Canada.
[3] P.J. Nixon, I. Sims, RILEM Recommended Test Method: AAR-2—Detection of Potential Alkali-Reactivity—Accelerated Mortar-Bar Test Method for Aggregates, in: P.J. Nixon, I. Sims (Eds.), RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS, Springer Netherlands, Dordrecht, 2016, pp. 61-77.
[4] Standards Australia, AS 1141.60.1 Methods for sampling and testing aggregates Method 60.1: Potential Alkali-Silica Reactivity-Accelerated Mortar Bar Method, Standards Australia Limited, Sydney, Australia, 2014.
[5] ASTM International, ASTM C1293 Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction, ASTM International, West Conshohocken, Pennsylvania, United States, 2020.
[6] Canadian Standards Association, CSA A23.2-14A Expansivity of Aggregates; Procedure for Length Change Due to Alkali-Aggregate Reaction in Concrete Prisms, Ontario, Canada.
[7] P.J. Nixon, I. Sims, RILEM Recommended Test Method: AAR-3—Detection of Potential Alkali-Reactivity—38 °C Test Method for Aggregate Combinations Using Concrete Prisms, in: P.J. Nixon, I. Sims (Eds.), RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS, Springer Netherlands, Dordrecht, 2016, pp. 79-97.
[8] Standards Australia, AS 1141.60.2 Methods for Sampling and Testing Aggregates Method 60.2: Potential Alkali-Silica Reactivity-Concrete Prism Method, Standards Australia Limited, Sydney, Australia, 2014.
[9] ASTM International, ASTM C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method), West Conshohocken, Pennsylvania, United States, 2013.
[10] Canadian Standards Association, CSA A23.2-28A Standard practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete, Ontario, Canada, 2009.
[11] M.D.A. Thomas, F.A. Innis, Use of the Accelerated Mortar Bar Test for Evaluating the Efficacy of Mineral Admixtures for Controlling Expansion due to Alkali-Silica Reaction, Cement, Concrete and Aggregates 21(2) (1999).

[12] M. Thomas, B. Fournier, K. Folliard, J. Ideker, M. Shehata, Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete, Cement and Concrete Research 36(10) (2006) 1842-1856.
[13] M.D.A. Thomas, B. Fournier, K.J. Folliard, M.H. Shehata, et al., Performance Limits for Evaluating Supplementary Cementing Materials Using Accelerated Mortar Bar Test, ACI Materials Journal 104(2) (2007) 115-122.
[14] K. Yamada, S. Karasuda, S. Ogawa, Y. Sagawa, M. Osako, H. Hamada, M. Isneini, CPT as an evaluation method of concrete mixture for ASR expansion, Construction and Building Materials 64 (2014) 184-191.
[15] J. Lindgård, Ö. Andiç-Çakır, I. Fernandes, T.F. Rønning, M.D.A. Thomas, Alkali–silica reactions (ASR): Literature review on parameters influencing laboratory performance testing, Cement and Concrete Research 42(2) (2012) 223-243.
[16] B. Fournier, C. Rogers, C. Macdonald, Multilaboratory study of the concrete prism and accelerated mortar bar expansion tests with Spratt aggregate, 14th International Conference on Alkali Aggregate Reaction, Austin, Texas, USA, 2012, pp. 1-10.
[17] V. Sirivivatnanon, J. Mohammadi, W. South, Reliability of new Australian test methods in predicting alkali silica reaction of field concrete, Construction and Building Materials 126 (2016) 868-874.
[18] Standards Australia, AS 3582.1: Supplementary cementitious materials - Fly ash, Sydney, Australia, 2016.
[19] Standards Australia, AS 3582.2: Supplementary cementitious materials - Slag - Ground granulated blast-furnace, Sydney, Australia, 2016.
[20] Standards Australia, SA HB 79:2015 Alkali Aggregate Reaction—Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia, Standards Australia Limited, 2015.
[21] Standards Australia, AS 3972 General Purpose and Blended Cements, Sydney, Australia, 2010.
[22] ASTM International, ASTM C1778 Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete, West Conshohocken, Pennsylvania, United States, 2020.
[23] B. Fournier, R. Chevrier, A. Bilodeau, P.-C. Nkinamubanzi, N. Bouzoubaa, Comparative Field and Laboratory Investigations on the Use of Supplementary Cementing Materials (SCMs) to Control Alkali-Silica Reaction (ASR) in Concrete, in: H.d.M. Bernardes, N.P. Hasparyk (Eds.) Proceedings of the 15th International Conference on Alkali-Aggregate Reaction in Concrete, The International Conference on Alkali-Aggregate Reaction (ICAAR), Sao Paulo, Brazil, 2016.
[24] B. Fournier, J. Lindgård, B.J. Wigum, I. Borchers, Outdoor exposure site testing for preventing Alkali-Aggregate Reactivity in concrete – a review, International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2018), MATEC Web of Conferences 2018.
[25] R.D. Hooton, C. Rogers, C.A. MacDonald, T. Ramlochan, Twenty-Year Field Evaluation of Alkali-Silica Reaction Mitigation, ACI Materials Journal 110(5) (2013) 539-548.
[26] M.D.A. Thomas, A. Dunster, P. Nixon, B. Blackwell, Effect of fly ash on the expansion of concrete due to alkali-silica reaction – Exposure site studies, Cem. Concr. Compos. 33 (2011) 359–367.
[27] American Association of State Highway and Transportation Officials, AASHTO PP65 Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction, 2011.
[28] K. Kerendis, D. Hooton, Mitigating Alkali-Silica Reaction when Using High-Alkali Cements, Concr. Int. (2011) 34-39.
[29] U. Costa, T. Mangialardi, A.E. Paolini, Minimizing alkali leaching in the concrete prism expansion test at 38^{o}C, Constr. Build. Mater. 146 (2017) 547–554.
[30] J. Lindgård, M.D.A. Thomas, E.J. Sellevold, B. Pedersen, Ö. Andiç-Çakır, H. Justnes, T.F. Rønning, Alkali–silica reaction (ASR)—performance testing: Influence of specimen pre-treatment, exposure conditions and prism size on alkali leaching and prism expansion, Cem. Concr. Res. 53 (2013) 68–90.

[31] M.J. Tapas, P. Thomas, K. Vessalas, V. Sirivivatnanon, Mechanisms of Alkali-Silica Reaction Mitigation in AMBT Conditions: Comparative Study of Traditional Supplementary Cementitious Materials, Journal of Materials in Civil Engineering 34(3) (2021) 04021460.
[32] M.J. Tapas, L. Sofia, K. Vessalas, P. Thomas, V. Sirivivatnanon, K. Scrivener, Efficacy of SCMs to mitigate ASR in systems with higher alkali contents assessed by pore solution method, Cement and Concrete Research 142 (2021) 106353.
[33] M. Thomas, The effect of supplementary cementing materials on alkali-silica reaction: A review, Cement and Concrete Research 41 (2011) 1224–1231.
[34] A. Leemann, Z. Shi, J. Lindgård, Characterization of amorphous and crystalline ASR products formed in concrete aggregates, Cement and Concrete Research 137 (2020) 106190.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Prof Vute Sirivivatnanon
Professor, University of Technology Sydney

Dr Paul Thomas
Senior Lecturer, University of Technology Sydney

Dr Marie Joshua Tapas
Research Associate, University of Technology Sydney

Dr Thuc Nhu Nguyen
Research Associate, University of Technology Sydney