Linking New Australian Alkali Silica Reactivity Tests to World-Wide Performance Data

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Abstract: The long awaited Australian Standard test methods to detect alkali-silica reactivity (ASR) of aggregates - AS 1141.60.1 accelerated mortar bar test (AMBT) and AS 1141.60.2 concrete prism test (CPT) - were published in September 2014. Both test methods were adopted correspondently from the ASTM 1260 and ASTM C1294 test methods but with different performance limits leading to a new class of slowly reactive aggregates. This paper reviews international and Australian research which supported these new performance limits. It also reviews and examines the value of these testing methods in predicting the ASR of aggregates in field-exposed large concrete blocks and a limited number of concrete structures. The outcomes may lead to a consideration of the hierarchy of these two test methods.

Keywords: AMBT, ASR, CPT, ASR performance limits,

1. Introduction

There main types of tests for evaluating the alkali-silica reactivity (ASR) of aggregates are accelerated mortar bar test (AMBT), concrete prism test (CPT) and field testing. Recently, Standards Australia CE-012 Aggregate and Rock for Engineering Purposes Committee has published two new standard test methods to detect potential ASR:

> AS 1141.60.1-2014 Potential alkali-silica reactivity - Accelerated mortar bar method (AMBT) [1] and AS 1141.60.2-2014 Potential alkali-silica reactivity - Concrete prism method (CPT) [2]

Accelerated mortar bar test (AMBT) is a rapid test method applied to determine the potential alkali-silica reactivity of aggregates by testing mortar specimens. In general, the procedure of mortar bar testing involves casting mortar bars (normally in the size of 25 x 25 x 285 mm) and curing for 24 hours in a relative humidity of at least 95%. Afterwards, mortar samples are kept in potable water and heated to 80°C and then mortar bars are put in the solution of 1N NaOH that is already at 80°C for 24 hours. After that, the initial length of mortar bars is measured as the zero reading. Until the next reading, samples remain in 1N NaOH for a period of time which can be 10, 14, 21 or 28 days according to the different standards and test methods.

During the development of the Standard AS 1141.60.1, three alternative AMBT methods namely the fixed flow (RMS T363 [3] or VicRoads CR376.03 [4]), fixed water-to-cement ratio (ASTM C1260 [5]) and fixed free water-to-cement ratio (RILEM AAR-2 [6]) were considered. The committee finally agreed to adopt the fixed water-to-cement ratio method because of the more conservative mortar mix composition in ASTM C1260 compared to the fixed flow method [7,8], reduced variability due to difficulty in determining the surface saturated dry condition (SSD) of crushed aggregates or flow measurement [9], and the possible benchmarking to international research data [10] and international proficiency program [11].

The procedure of Australian Standard AS 1141.60.1 is adopted from the ASTM C1260. In a recent study, Fournier et al [11] investigated the proficiency of different AMBT test procedures, including the American ASTM, Canadian CSA and the European RILEM test methods. It should be noted that the test procedure for ASTM and CSA tests are similar. As can be seen from **Table 1** coefficients of variation of AMBT methods showed a lower variation in the 14 days expansion for the ASTM and CSA methods compared to the RILEM test results. However, similar variations in the 28 days expansion were observed for all three test methods. By considering the 10 and 21 days limits for measuring the expansion of mortar samples in AS 1141.60.1, the outcome of Fournier et al investigation provides support for the adoption of ASTM procedure.

Table 1: Statistical analysis of different accelerated mortar bar test [11]

Test age	Method of testing	Number of results	Mean [%]	Standard deviation	Coefficient of variation [%]	Min [%]	Max [%]
14 days	ASTM	26	0.375	0.043	11.6	0.307	0.486
	CSA	24	0.374	0.055	14.8	0.206	0.451
	ASTM + CSA	50	0.375	0.049	13.1	0.206	0.486
	RILEM	3	0.291	0.071	24.5	0.230	0.369
28 days	ASTM	26	0.591	0.067	11.3	0.450	0.725
	CSA	24	0.571	0.064	11.2	0.470	0.700
	ASTM + CSA	50	0.582	0.066	11.3	0.450	0.725
	RILEM	3	0.547	0.065	11.9	0.500	0.621

In addition, Thomas and Innis [12] stressed that the usefulness of various tests may be judged on the basis of the ease of testing, the repeatability or precision of the outcomes, the time taken to complete the test and, ultimately, the ability of the test to predict behaviour in the field.

Concrete prism test (CPT) is considered a more reliable test method than the accelerated mortar bar tests in the literature. The reason that the CPT test may provide a better measure for determining ASR compared to the AMBT test is that the CPT test samples are prepared using a concrete mix, and kept in less aggressive conditioning and lower temperature for a longer period of time. Moreover, CPT samples are larger in size (normally in the size of 75 x 75 x 285 mm). Another difference between CPT and AMBT test is related to the procedure of providing the available alkali for ASR reaction. While in the AMBT test mortar bars are kept in NaOH solution whereas in the CPT test the alkali content in the concrete was arbitrarily raised during mixing. For example the ASTM C1293 test measures the expansion of concrete prisms with a cement content of 420±10 kg/m^3 and a dry mass of coarse aggregate per unit volume of concrete equal to 0.70±0.02 of its dry-rodded bulk density with a water to cementitious material ratio (w/cm) of 0.42 to 0.45 by mass. The cement has a total alkali content of 1.25% of Na_2O_{eq} equivalent by mass of cement. Specimens are placed in a container stored in a 38.0±2°C. Expansion measurements are performed up to 52 weeks for CPT samples. In addition, for samples prepared with supplementary cementitious materials (SCMs) to mitigate potential ASR, it is recommended in the CSA method to extend the test duration up to 104 weeks. Standard AS 1141.60.2 is adopted from ASTM C 1293 [13] procedure however there are differences in the interpretation of test results between both standards.

Field testing (Outdoor exposure) provides the most realistic condition for ASR testing. Outdoor exposure can simulate the temperature and moisture cycling. In addition, by conducting field tests, samples with larger dimensions can be casted that are closer to the scale of real structures. In addition, outdoor samples can be evaluated for longer periods of time (5 to 20 years).

It is implied by the literature [14] that the best method to determe whether an aggregate is potentially reactive or innocuous is to study the history of aggregates field performance. An aggregate can be used in concrete provided that satisfactory field performance was achieved and the cement content (the total alkali content of the cement) should be the same or higher in the field concrete than that proposed in the new structure. The outdoor field exposed concrete should be at least 10 years old. In addition, the exposure conditions of the field concrete should be at least as severe as those in the proposed structure [14].

2. Performance Limits

In both the AMBT and CPT methods, expansion limits after a particular period are used to indicate/classify the potential reactivity of aggregates tested. These expansion performance limits were derived from research and field experiences with the use of a wide range of aggregates.

2.1. Accelerated Mortar Bar Test (AMBT)

Shayan and Morris [7] compared the accelerated mortar bar expansion of 18 aggregates of known service record, based on the RMS T363 and ASTM C1260, and found lower expansion of the RMS mortars than the corresponding ASTM mortars for reactive aggregates. The lower expansion of the RMS mortars may be due to the lower water/cement ratio in the range of 0.40-0.42 in RMS T363 compared to 0.47 used in the ASTM method. The mortar bar expansions are similar for the less reactive aggregates possibly because they consume less alkali and are not affected by the differences in supply of alkali in the two methods. They found both test methods and their corresponding expansion limits to be capable of assessing the alkali reactivity of non-reactive or very reactive aggregates. However for slowly reactive aggregates, both methods can be used provided that the RMS expansion limits, reproduced in **Table 2**, are used to interpret the reactivity of the aggregates.

It was also found that the two methods would produce similar assessments for the effectiveness of fly ash in controlling ASR expansion for all except the very reactive aggregates. For such reactive aggregates, both methods could be used to obtain expansion curves but the RTA limits were recommended for the interpretation of the adequacy of the amount of fly ash used in controlling the expansion.

Table 2: Aggregate reactivity classification in accordance with RTA T363 [7]

Mortar Bar Expansion in 1M NaOH (80°C) [%]		Classification
10 days	21 days	
< 0.10*	< 0.10*	Non-reactive
< 0.10*	≥ 0.10*	Slowly reactive
≥ 0.10*	(much greater than) ≫ 0.10*	Reactive

* For naturally occurring fine aggregates the limit is 0.15%

The non-mandatory appendix in ASTM C1260 provides guidance to the interpretation of test results with the following expansion limits: 14-day expansions of less than 0.10% to be indicative of "innocuous" behaviour whereas 14-day expansions of more than 0.20% are indicative of "potentially deleterious" expansion. Aggregates with 14-day expansion between 0.10% and 0.20% are known to be either innocuous or deleterious in field performance, and supplemental information in the form of petrographic examination or identification of alkali reaction products in specimens after tests, or field service record can be used in the assessment of the performance. It is noted in the same appendix that some granitic gneisses and metabasalts have been found to be deleteriously expansive in field performance, even though, their expansion in the test was less than 0.10%.

Table 3 Comparison of ASTM and AS 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%		< 0.30%
Potential deleterious	≥ 0.2*%	Reactive	≥ 0.10%	or	≥ 0.30%

ASTM C1260 performance limits are compared with the Australian Standard AS 1141.1 limits in **Table 3**. The AS 1141.60.1 classifies aggregates with 21-day expansion below a lower limit of 0.10% to be non-reactive, and those with 10-day expansion equal or greater than the lower limit of 0.10% or 21-day expansion equal or greater than the upper limit of 0.30% to be reactive. For aggregates with 10-day expansion below the lower limit of 0.10% but 21-day expansion equal to or exceeding the lower limit of 0.10% but not exceeding the upper limit of 0.30% to be a "slowly reactive" aggregate. Note that the lower limit applicable to natural sand is 0.15%.

2.2 Concrete prism method (CPT)

The non-mandatory ASTM appendix states that an aggregate might reasonably be classified as potentially deleteriously reactive if the average expansion of three concrete specimens is equal to or greater than 0.04% at one year. CSA indicated similar 0.04% expansion for determining ASR however, compared to the non-mandatory ASTM approach CSA has a more definitive approach (ASTM C1293 [13], CSA A23.2-27A-02 [15]). It is also suggested in CSA A23.2-28A-02 that the amount of pozzolan or slag used in combination with an aggregate is a least the minimum needed to prevent excessive expansion in field concrete if the average expansion is less than 0.04% at two years [16]. Similarly, the Standard ASTM C1293 confirmed the two years test duration.

In Australia, AS 1141.60.2 uses essentially the same concrete mix proportion and test method as the ASTM C1293 but classifies an aggregate with a prism expansion of less than 0.03% at 52 weeks as "non-reactive" and an aggregate with a prism expansion equal to or greater than 0.03% at 52 weeks as "potentially reactive". The lower expansion limit is considered more conservative as it was adopted from the RMS T364 which tests concrete with a higher adjusted cement alkali of 1.38% of Na_2Oeq equivalent. For mitigation, the standard does not state any particular limit but refer to classification contained in the supply agreement.

2.3 Hierarchy of test methods

There has been no agreed hierarchy of the two Australian Standard test methods. RMS T363 noted that some glassy basalt may cause excessive mortar bar expansion, due to the production of fine glassy particles in the fine aggregate grading required for mortar bars. The reactivity of coarse aggregate of the same source needs to be verified, because the glassy phase within compact coarse basalt aggregates may not be accessible to alkali and may not cause excessive concrete expansion. Concrete prism tests in accordance with RMS T364 or concrete block tests may be required for this purpose.

3. Australian and International Research

3.1 Consistency of AMBT & CPT reactivity classification

3.1.1 Improved AMBT performance limits in AS 1141.60.1

Table 4 presents alkali-silica reaction data from the investigation conducted by Stark [17]. ASTM C1260 limits were applied to check the potential alkali-silica reactivity of aggregates within two weeks. According to the ASTM C1260 limits, aggregates showing 14-day expansions exceeding 0.1% should be classified as being potentially deleterious aggregates and were labelled "reactive" in **Table 4**. Moreover, aggregates that showed 14-day expansions lower than 0.1% were classified as "innocuous".

Table 4 Comparison of ASTM and AS mortar bar expansion

ID	Rock type	Field Performance	Expansion			ASTM 1260	AS 1141.60.1
			10 Days	14 Days	21 Days		
1	Granitic Volcanic	Reactive	0.713	0.867	1.035	Reactive	Reactive
2	Granitic Volcanic	Reactive	0.375	0.424	0.5	Reactive	Reactive
3	Argillite	Reactive	0.354	0.418	0.511	Reactive	Reactive
4	Chert, Quartzite	Reactive	0.328	0.409	0.515	Reactive	Reactive
5	Chert, Quartzite	Reactive	0.246	0.314	0.416	Reactive	Reactive
6	Granitic Gneiss	Reactive	0.239	0.309	0.385	Reactive	Reactive
7	Quartzite	Reactive	0.17	0.225	0.312	Reactive	Reactive
8	Chert, Quartzite	Reactive	0.116	0.177	0.27	Uncertain	Reactive
9	Chert, Quartzite	Reactive	0.073	0.106	0.142	Uncertain	Slow-Reactive
10	Granitic Gneiss	Reactive	0.065	0.096	0.132	Innocuous	Slow-Reactive
11	Granitic Gneiss	Reactive	0.064	0.086	0.124	Innocuous	Slow-Reactive
12	Metavolcanics	Reactive	0.052	0.082	0.115	Innocuous	Slow-Reactive
13	Limestone	Innocuous	0.029	0.026	0.035	Innocuous	Innocuous
14	Dolomite	Innocuous	0.066	0.066	0.077	Innocuous	Innocuous
15	Gabbro	Innocuous	0.029	0.044	0.066	Innocuous	Innocuous
16	Mixed Siliceous	Innocuous	0.181	0.278	0.329	Reactive	Reactive
17	Gabbro	Innocuous	0.061	0.075	0.157	Innocuous	Slow-Reactive

The last column demonstrates the interpretation of the results based on the Australian Standard criteria. As can be seen, the AS 1141.60.1 limits provided a significantly better understanding of the aggregate performance. ASTM C1260 failed to provide the correct interpretation for the performance of aggregates No 8 to 12. However, the Australian Standard criteria showed the reactivity of those aggregates and classified them as “reactive” or “slow-reactive”. Overall, the ASTM C1260 limit failed to classify 6 aggregates correctly out of the total 17 tested aggregates (aggregate identification 8-12 and 16). On the contrary, the Australian limits failed to provide a correct performance only for two aggregates (identification 16 and 17). From the given data, it can be seen that the Australian limits provided a more accurate understanding of the aggregates ASR performance.

Table 5 presents another set of data from the research conducted by Touma in The University of Texas at Austin [14]. Datasets presented in **Table 5** includes mortar and concrete expansion test in accordance with the ASTM C1260 and C1293, respectively. Tests were conducted to evaluate 15 types of aggregates while the field performances of aggregates were known. As can be seen from **Table 5** the ASTM C1260 (mortar test) failed to provide the correct interpretation for the performance of aggregates (8, 9, 10, 12 and 14). However, the Australian Standard criteria indicated a correct reactivity performance for some of those aggregates and classified them as “reactive” or “slowly-reactive”. Overall, the ASTM C1260 limit failed to classify 6 aggregates correctly out of the total 15 tested aggregates. In contrast, the Australian limits failed to provide a correct performance for only two aggregates (12 and 14). From the given data it is concluded that the Australian limits for mortar test provide a more reliable understanding of aggregates ASR performance.

Table 5 Comparison of ASTM and AS mortar bar and concrete prism expansion

ID	Aggregate	Expansion [%]				Field Performance	Classification			
		Mortar			Concrete		ASTM C1260	AS 1141.60.1	ASTM C1293	AS 1141.60.2
		11-day	14-day	21-day	52-week					
1	Rhyolite	0.21	0.24	0.31	0.073	Reactive	Reactive	Reactive	Reactive	Reactive
2	Rhyolite	0.27	0.29	0.34	0.107	Reactive	Reactive	Reactive	Reactive	Reactive
3	Quartzite, sandstone, limestone	0.75	0.79	0.89	0.379	Reactive	Reactive	Reactive	Reactive	Reactive
4	Rhyolite, andesite	0.83	0.91	1.04	0.411	Reactive	Reactive	Reactive	Reactive	Reactive
5	Argillite	0.28	0.31	0.39	0.085	Reactive	Reactive	Reactive	Reactive	Reactive
6	Pink granite, quartz, chert	0.23	0.28	0.39	0.051	Reactive	Reactive	Reactive	Reactive	Reactive
7	Quartz, chert	0.19	0.26	0.40	0.043	Reactive	Reactive	Reactive	Reactive	Reactive
8	Feldspar, quartz, chlorite	0.09	0.11	0.16	0.046	Reactive	Uncertain	Slowly-Reactive	Reactive	Reactive
9	Quartz, granitic rock	0.11	0.15	0.25	0.040	Reactive	Uncertain	Reactive	Reactive	Reactive
10	Quartzite, pyroxene, sericite	0.14	0.17	0.24	0.053	Reactive	Uncertain	Reactive	Reactive	Reactive
11	Dolomite	0.02	0.02	0.03	0.022	Innocuous	Innocuous	Innocuous	Innocuous	Innocuous
12	Glacial deposit, shale	0.38	0.25	0.44	0.025	Innocuous	Reactive	Reactive	Innocuous	Innocuous
13	Natural siliceous and glassy	0.18	0.25	0.34	0.060	Reactive	Reactive	Reactive	Reactive	Reactive
14	Natural siliceous	0.20	0.42	0.53	0.022	Innocuous	Reactive	Reactive	Innocuous	Innocuous
15	Rhyolite, andesite	0.33	0.36	0.46	0.064	Reactive	Reactive	Reactive	Reactive	Reactive

3.1.2 Consistency of both CPT classifications with field performance

The concrete prism test results for expansion of prisms in 52 weeks showed the ASTM C1293 criterion could accurately decide on the reactivity performance of aggregates. Using the ASTM C1293 0.04% expansion limit, all 15 aggregates were classified correctly regarding their performance. Similarly, the Australian Standard AS 1141.60.2 limit provided correct reactivity performance for all the aggregates. Results showed that there is no difference in the outcome of using the AS 1141.60.2 expansion limit (0.03 expansion over 52 weeks) and the ASTM C1293 expansion limit (0.04 expansion over 52 weeks). In addition, the assessment of data indicated a more reliable outcome for concrete prism test compared to the mortar bar test for both ASTM and the Australian test methods.

3.1.3 Relative value of AMBT and CPT methods

It is reported by Lane [18] that alkali-silica reaction has been a major cause of the deterioration for several concrete structures in Virginia. Lane examined the occurrence of the reaction in several Virginian structures. **Table 6** summarised the reactivity performance for the 13 aggregates. As can be seen the aggregate evaluation based on the ASTM C1260 provided a correct decision on reactivity of some of the aggregates.

Table 6 Comparison of ASTM mortar bar expansion and field performance

ID	Rock Type	Field Performance	Expansion 14 Days	ASTM 1260
1	Dolomitic Limestone	Undetermined	0.23	Reactive
2	Argillaceous Dolomite	Innocuous	0.09	Innocuous
3	Diabase	Innocuous	0.13	Reactive
4	Quartzose Sand	Undetermined	0.09	Reactive
5	Quartzose Gravel	Undetermined	0.12	Reactive
6	Quartzose Sand	Reactive	0.19	Reactive
7	Quartzose Gravel	Reactive	0.32	Reactive
8	Metarhyolite	Reactive	0.39	Reactive
9	Qartzite	Undetermined	0.30	Reactive
10	Acrch Marble Calc Chist	Reactive	0.17	Reactive
11	Granite Gneiss	Suspected	0.17	Reactive
12	Granite Gneiss	Reactive	0.07	Reactive
13	Greenstone Metabasalt	Reactive	0.08	Reactive

Except for aggregate No 3 there is no disagreement between the field performance and ASTM C1260 mortar test results. For some aggregates with unknown field performance, ASTM C1260 classified them as “reactive”. However, the only notable drawback from the ASTM C1260 test is that it is significantly conservative and as can be seen from **Table 6** ASTM C1260 labelled performance of the most unknown aggregates as “reactive”.

The National Aggregate Association (NAA) performed the ASTM C1293 and ASTM C1260 tests on several aggregates. Results of this testing program was reported by Touma [14]. As can be seen from the listed results in **Table 7** there is no strong correlation between the outcome of ASTM C1260 and C1293. For 12 aggregates, results of ASTM C1260 test could not confirm the evaluation of ASTM C1293. In addition, for 8 aggregates there is a conflict between ASTM C1260 and C1293 interpretation. It is noted that the interpretation of test results at 14 days resulted in a conservative interpretation and led to labelling several aggregates as “reactive”. In addition, except for one aggregate (aggregate No 14), all other results showed that there is no difference in the outcome of using the AS 1141.60.2 expansion limit (0.03% expansion over 52 weeks) and the ASTM C1293 expansion limit (0.04% expansion over 52 weeks). It can be noted that the lower expansion limit based on the Australian CPT method did not make difference in the interpretation of the test results.

Table 7 Comparison of ASTM and AS mortar bar and concrete prism expansion

ID	Rock type	Expansion [%]		Classification		
		Mortar 14 days	Concrete 1year	ASTM C1260	ASTM C1293	AS 1141.60.2
1	Limestone	0.252	0.083	Reactive	Reactive	Reactive
2	Siliceous, Dolomite	0.227	0.009	Reactive	Innocuous	Innocuous
3	Dolomite, Siliceous	0.159	0.020	Uncertain	Innocuous	Innocuous
4	Limestone	0.285	0.015	Reactive	Innocuous	Innocuous
5	Limestone	0.335	0.070	Reactive	Reactive	Reactive
6	Siliceous	1.061	0.196	Reactive	Reactive	Reactive
7	Limestone	0.041	0.016	Innocuous	Innocuous	Innocuous
8	Siliceous	0.210	0.012	Reactive	Innocuous	Innocuous
9	Siliceous	0.139	0.018	Uncertain	Innocuous	Innocuous
10	Siliceous	0.250	0.012	Reactive	Innocuous	Innocuous
11	Siliceous	0.678	0.026	Reactive	Innocuous	Innocuous
12	Siliceous	1.072	0.016	Reactive	Innocuous	Innocuous
13	Siliceous	0.080	0.008	Innocuous	Innocuous	Innocuous
14	Dolomite, Limestone, Siliceous	0.154	0.038	Uncertain	Innocuous	Reactive
15	Siliceous	0.279	0.007	Reactive	Innocuous	Innocuous
16	Siliceous	0.316	0.005	Reactive	Innocuous	Innocuous

A research conducted by Berube [19] showed that even though the AMBT test was capable of detecting numerous of reactive aggregates, it was too severe for many aggregates that have performed well when tested using the concrete prism method and that have performed well in the field. Accordingly, it is stated that the ASTM C1260 should not be applied for rejecting aggregates.

3.1.4 Effect of different performance limits in AS 1141.60.2 and ASTM C1293

Test results from Berube [19] investigation are presented in **Table 8**. It can be seen that the ASTM C1293 CPT could accurately predict the field performance of reactive aggregates. In addition, except for one aggregate (aggregate identification 9) there is no conflict between the interpretation of AS 1141.60.2 and ASTM 1293. This outcome confirm the fact that the AS 1141.60.2 lower limit provides no difference in the interpretation of test results.

Table 8 Comparison of ASTM (CSA) and AS mortar bar and concrete prism expansion

ID	Aggregate type	Field performance	Expansion [%]		Classification		
			AMBT 14 days	CPT 52 weeks	ASTM 1260	ASTM 1293	AS 1141.60.2
1	Andesite	Innocuous	0.26	0.02	Reactive	Innocuous	Innocuous
2	Anorthosite	Innocuous	0.04	0.02	Innocuous	Innocuous	Innocuous
3	Basalt	Innocuous	0.03	0.01	Innocuous	Innocuous	Innocuous
4	Charnockite	Innocuous	0.02	0.01	Innocuous	Innocuous	Innocuous
5	Hornfel	Innocuous	0.22	0.02	Reactive	Innocuous	Innocuous
6	Hornfel	Innocuous	0.23	0.01	Reactive	Innocuous	Innocuous
7	Diorite	Innocuous	0.02	0.01	Innocuous	Innocuous	Innocuous
8	Gabbro	Innocuous	0.20	0.02	Uncertain	Innocuous	Innocuous
9	Granitic gneiss	Innocuous	0.05	0.03	Innocuous	Innocuous	Reactive
10	Granite	Innocuous	0.02	0.01	Innocuous	Innocuous	Innocuous
11	Greywacke	Innocuous	0.19	0.02	Uncertain	Innocuous	Innocuous
12	Greywacke	Innocuous	0.20	0.01	Uncertain	Innocuous	Innocuous
13	Potsdam sandst	Reactive	0.07	0.07	Innocuous	Reactive	Reactive
14	Phonolite	Innocuous	0.02	0.02	Innocuous	Innocuous	Innocuous
15	Quartzite	Innocuous	0.01	0.01	Innocuous	Innocuous	Innocuous
16	Chloritic schist	Reactive	0.19	0.05	Uncertain	Reactive	Reactive
17	Siliceous shale	Reactive	0.34	0.09	Reactive	Reactive	Reactive
18	Syenite	Innocuous	0.01	0.01	Innocuous	Innocuous	Innocuous
19	Rhyolitic tuff	Reactive	0.35	0.25	Reactive	Reactive	Reactive
20	Rhyolitic tuff	Reactive	0.25	0.09	Reactive	Reactive	Reactive
21	Rhyolitic tuff	Reactive	0.27	0.05	Reactive	Reactive	Reactive
22	Granitic sand	Innocuous	0.02	0.01	Innocuous	Innocuous	Innocuous
23	Lithic gravel/sand	Innocuous	0.26	0.02	Reactive	Innocuous	Innocuous
24	Carb sandstone	Innocuous	0.12	0.02	Uncertain	Innocuous	Innocuous

Figure 1 is plotted based on the shown data in **Table 8.** It shows the effectiveness of the CPT results compared to AMBT results. CPT recognised most of the known reactive aggregates (aggregates 13, 16, 17, 19, 20 and 21 are reactive based on field performance), however, it did not misclassify other “innocuous” aggregates as “reactive”.

it can be seen that the AMBT has a conservative and incorrect interpretation for some aggregates such as No 1, 5, 6 and 23 which resulted in classifying these aggregates as “reactive”, while they are not reactive. On the other hand, the grey highlighted area of **Figure1** implies that most of the aggregates classified “uncertain” were “innocuous”, except for aggregate 16. Moreover, aggregate 13 labelled innocuous by AMBT test while it is a reactive aggregate based on field performance and CPT results. Although AMBT is not a time-consuming test compared to the CPT, it is a good measure only for highlighting the innocuous aggregates. AMBT is conservative and due to the aggressive nature that this test has, it labels some innocuous aggregates as “reactive” or “uncertain”, accordingly, no aggregate is suggested to be rejected by this test. It is suggested that the complementary CPT data could provide a more reliable understanding of aggregates reactivity. Another shortcoming of the ASTM AMBT test is the 14-day limits. These limits could not provide any clear classification for several numbers of aggregates. In that case, other testing methods such as CPT or field data would be required for a reliable decision-making.

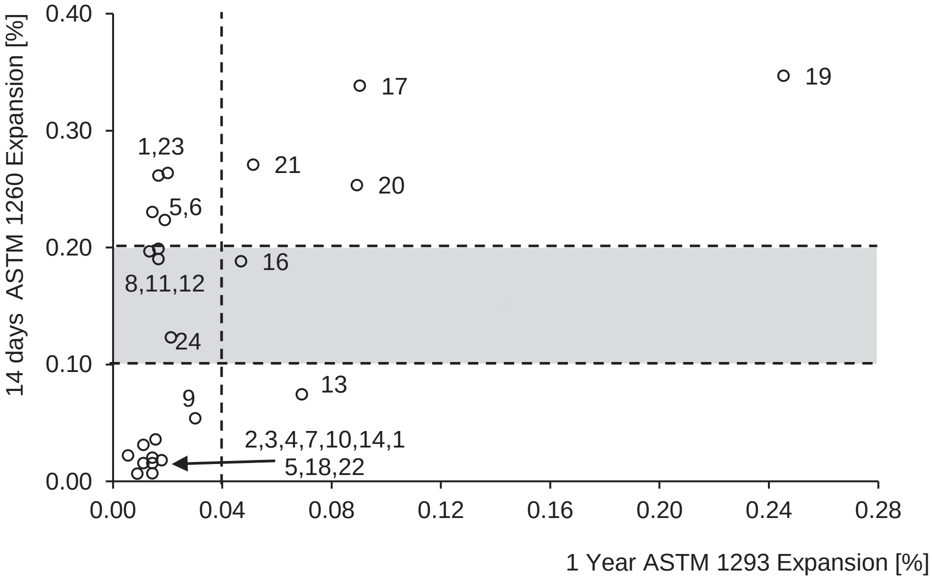

Figure1: CPT vs AMBT test results [19]

Ideker et al. [10] recently reported expansion data of ASTM C1260, ASTM C1293 and exposure concrete blocks made from 8 fine aggregates and 17 coarse aggregates as presented in **Table 9**. The mortar bar and concrete prism results were calibrated to those obtained from the large 710x380x380 mm concrete blocks exposed outdoor at the University of Texas in Austin.

Table 9 Comparison of ASTM, AS, and exposure block results

ID	Mineralogy	Expansion [%]			Classification			
		AMBT 14-day	CPT 1-year	Field block Exposure[2]	ASTM 1260	ASTM 1293	AS 1141.60.2	Field Exposure
F1[1]	Mixed quartz/chert/feldspar	0.64	0.586	1.239	Reactive	Reactive	Reactive	Reactive
F2	Mixed quartz/chert sand	0.31	0.119	0.991	Reactive	Reactive	Reactive	Reactive
F3	Quartz sand	0.29	0.057	0.487	Reactive	Reactive	Reactive	Reactive
F4	Quartz	0.28	0.059	0.575	Reactive	Reactive	Reactive	Reactive
F5	Quartz	0.17	0.038	0.333	Uncertain	Reactive	Innocuous	Reactive
F6	Tan dolomite carbonate	0.02	0.014	-	Innocuous	Innocuous	Innocuous	Reactive
F7	Mixed quartz/chert sand	0.29	0.207	1.363	Reactive	Reactive	Reactive	Reactive
F8	Mixed sand/gravel	0.29	0.111	0.582	Reactive	Reactive	Reactive	Reactive
C1	Chert & quartzite	0.02	0.129	0.212	Innocuous	Reactive	Reactive	Reactive
C2	Tan dolomite carbonate	0.33	0.112	0.315	Reactive	Reactive	Reactive	Reactive
C3	Limestone	0.11	0.055	0.141	Uncertain	Reactive	Reactive	Reactive
C4	Tan dolomite (marble)	0.14	0.020	0.119	Uncertain	Innocuous	Innocuous	Reactive
C5	Mixed quartz/chert	0.09	0.085	0.133	Innocuous	Reactive	Reactive	Reactive
C6	Tan dolomite (marble)	0.02	0.006	-	Innocuous	Innocuous	Innocuous	Reactive
C7	Limestone	0.37	0.204	0.379	Reactive	Reactive	Reactive	Reactive
C8	Mixed mineralogy gravel	0.31	0.144	0.368	Reactive	Reactive	Reactive	Reactive
C9	Chert	0.0	0.149	0.212	Innocuous	Reactive	Reactive	Reactive
C10	Rhyolite volcanic rocks	0.82	0.159	0.421	Reactive	Reactive	Reactive	Reactive
C11	Granodiorite & metadacite	0.08	0.086	0.220	Innocuous	Reactive	Reactive	Reactive
C12	Quartzite	0.14	0.163	0.183	Uncertain	Reactive	Reactive	Reactive
C13	Quartzite	0.12	0.098	0.271	Uncertain	Reactive	Reactive	Reactive
C14	Granite & quartzite gravel	0.23	0.097	0.294	Reactive	Reactive	Reactive	Reactive
C15	Rhyolite/mixed quartz	0.40	0.158	0.191	Reactive	Reactive	Reactive	Reactive
C16	Granite, meterhyolite	0.06	0.047	0.056	Innocuous	Reactive	Reactive	Reactive
C17	Greywacke	0.44	0.162	0.225	Reactive	Reactive	Reactive	Reactive

[1] F= Fine aggregates and C= Coarse aggregates, [2] Na_2O_{eq}=1.25%

It was found that the AMBT was a good indicator of reactivity of some aggregates. However, the concrete prism test could provide a more reliable evaluation of the most aggregates. In some cases, the results from the CPT disagreed with those from the AMBT. Ideker indicated that in no reported cases of deleterious expansion in the field, concretes containing aggregates that have passed the ASTM C1293 [10]. This evidence supports the better correlation between the reactivity diagnosed by CPT and reactivity in field exposure.

It is possible to re-evaluate the expansion data based on the performance criteria recommended in AS1141.60.2. It was found that except for aggregate F5, the proposed AS1141.60.2 would have classified all aggregate in a similar classification. However, the lowering of the CPT limit from 0.04% to 0.03% would have made no difference to the prediction. The results do not support the use of the lower 0.03% limit in the draft AS1141.60.2. They also show the exposure blocks to be a very useful calibration tool for the laboratory test methods.

3.2 Australian (AS) classification

In Australia, Shayan [20] tested five Australian aggregates with field evidence to be slowly-reactive using two accelerated mortar bar test methods. The ASTM C1260 classes them as non-reactive or uncertain while the RTA T363 correctly classified such aggregates as slowly-reactive aggregates. It was suggested that the Australian acceptance limit of <0.1% expansion at 21 days of storage in 1 *M* NaOH solution at 80ºC be adopted by ASTM C1260 or that its 14-day expansion limit be lowered from 0.10% to 0.08%. The 300mm cube blocks showed large expansion or map-cracking usually after more than 1 year of exposure.

Table 10 Summary of data from Shayan [20]

Structure	Prism Expansion after 1 year	Comments
Australian Railway sleepers. Gneissic granite rocks which produced about 0.10% expansion at 21 days in the AMBT	Prism in 50ºC in water 0.06% with 1.4% alkali 0.09% with 1.9% alkali	300mm cube Block in 50ºC in water 0.12% with 1.4% alkali 0.18% with 1.9% alkali
Canning dam, WA. Gneissic granite rocks	Just >0.05%	Blended cements: 44%HVFA, 42%FA/4.2%SF triple blend shown to reduce expansion below 0.04%.
Dam 1 gneissic quartz gravel. Tests conducted on 3 reactive quartz gravels No 1-3	No 1 just < 0.03% No 2 & 3 well < 0.03% RTA T363 classified aggregate No 1-3 as reactive.	Aggregate No 1 blocks in 38ºC in water showed low expansion at 1 year but increased significantly at 2 years.
Dam 2 gneissic granite containing strained and microcrystalline quartz.	No CPT results.	Reactive aggregate as tested by RTA T363.
Dam 3 phyllite aggregate UY	Prism 0.019% at 1 year	410kg/m^3 cement with 1.76% alkali Block 0.117% at 1 year

Accordingly, the one-year concrete prisms test duration might not be enough for classifying the aggregates and may need to be extended. Results of the prism tests and field performance are summarised in **Table 10**. Using supplementary cementitious materials (SCMs) in mix designs is a common practice nowadays. It is important to take into account that the ASTM C1293 recommended the extension of the CPT duration to two years when SCMs are applied for mitigating the ASR. The two years test duration provides a more reliable time framework for evaluating the effect of the mitigation on slowly-reactive or reactive aggregates. This duration is supported by the observations of Shayan [20].

3.3 Slowly reactive aggregates

The term “slowly-reactive aggregate” has been introduced since 90s and is extensively used through literature [7,17,19–26]. However, lack of an existing appropriate test method or test limits for detecting ASR is observed throughout previous studies. It is significantly important to apply a reliable ASR test method, which can provide expansion limits for classification of aggregates as “non-reactive”, “slowly reactive” or “reactive” [20].

Some studies have shown the field evidence regarding the inability of ASTM 1260 14-day limit (expansion greater than 0.10%) for detecting slowly-reactive aggregates [27]. The failure in detecting slowly-reactive aggregate could cause serious damage to concrete structures in the long-term. In Australia, it is reported that meta-basalts or granitic gneisses cause serious damage to major structures [20]. In addition, studies in the United States showed that the slowly reactive aggregates could pass the existing AMBT tests but result in failure in field structures. These aggregate mostly included quartzites, gneisses, and schists [17]. For this reason, the AMBT test needs to be revised when slowly reactive aggregates are tested [28].

The proposed procedure should be rapid, requiring preferably not more than 28 days. Also the procedure should reliably discriminate between innocuous and slowly reactive as well as highly reactive aggregates [17]. In one study, it is recommended to extend the AMBT test duration up to 90 days and with the expansion limit of 0.20% to correctly classify the slowly-reactive aggregates [28]. Another suggested method is amongst the RILEM methods particularly the AAR-4 reactor method, which claimed to be as the proper method for identifying the reactivity of the slowly-reactive aggregate [23].

The Standard AS 1141.60.1 applies new limits to detect the "slowly-reactive" aggregates. The current CCAA research found a number of aggregates as "slowly-reactive". The clear limits of AS 1041.60.1 classified these aggregate "slowly-reacted" instead of classifying them as "uncertain". The slowly reacted aggregates can be utilised in concrete production while the proper ASR mitigation such as addition of SCMs to mix design is selected. In the case of slowly-reacted detection, it is suggested by this paper that the mitigation solution be tested by conduction the AS 1141.60.2 over the period of 2 years. This suggestion is supported by literature as it shown the CPT test could provide a more reliable indication of the performance of aggregates and the two years duration of testing will determine if the applied mitigation is effective to control the prism expansion to lower than 0.03%.

The test results proved that the proposed limits could distinguish between some innocuous and slowly-reactive aggregates. The Australian test method limits will enable the designer and concrete producer to distinguish slowly-reactive aggregates and safely use them in mix design by including the appropriate mitigation strategy. This approach is more efficient in term of asset management and provides a wider access to resources (local aggregates), which guarantees the more sustainable production of concrete. It is suggested by this research that the Australian test framework needs to provide an agreed hierarchy of the two Australian Standard test methods. This can help resolving issues when there is a conflict between the test results AS 1141.60.1 AMBT and AS 1141.60.2 CPT classifications.

4. Conclusions

Evaluation of the international and Australian test results by the Australian mortar bar (AS 1141.60.1) and concrete prism (AS 1141.60.2) tests support the reliability of both tests for determining the alkali-silica reactivity (ASR) of most aggregates and can be actively used by local industry.

Both the Australian and the ASTM mortar bar tests are quick and reliable means for determining non-reactive (innocuous) aggregates. However, the evaluation procedures of these test methods were found to be conservative and should not be applied for rejecting aggregates. In addition, international data for aggregates with known field reactivity showed that the Australian 1141.60.1 AMBT evaluation procedure is more reliable compared to the ASTM 1260 14-day limits.

Literature showed that the concrete prism test (CPT) has a better correlation with the performance of aggregates in field. The majority of international data showed that for cases which there are conflicts between AMBT and CPT classifications, the recommended approach was to accept the CPT test results. In addition, literature indicated that the 1-year expansion duration may not be sufficient, especially if supplementary cementitious materials (SCMs) are used for mitigating the ASR. In this case, it is suggested to extend the duration concrete prism testing up to two years in AS 1141.60.2

CPT test results indicated that there is no conflict between the Australian and ASTM CPT classifications. Although the Australian test procedure applies the lower 1-year expansion limit of 0.03%, however, there is no significant change observed in the outcomes of the both procedure. For this reason, it is suggested that the selected 1-year expansion limit of 0.03% may be increased to 0.04%.

There is a need for an extensive examination of available Australian and International data so that an agreement can be reached on the hierarchy of the two Australian Standard test methods. This can help resolving issues when there is a conflict between the AS 1141.60.1 AMBT and AS 1141.60.2 CPT classifications.

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