THE USE OF ACCELERATED MORTAR BAR EXPANSION RATES AND REACTION KINETIC MODEL IN DETECTING ALKALI-SILICA REACTIVE AGGREGATES

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Abstract

Two new Australian Standard test methods to detect alkali-silica reactivity (ASR) of aggregates: AS1141.60.1 Accelerated Mortar Bar Test (AMBT) and AS1141.60.2 Concrete Prism Test (CPT); were published in September 2014. Both test procedures were adopted correspondently from the ASTM C1260 and ASTM C1293 test methods but with different performance limits. The use of short-term AMBT expansion rates between 10 to 21 days have been found effective in classifying non-reactive, slowly reactive and reactive aggregate in better agreement to the performance of most of the reported outdoor-exposed large concrete blocks or field structures. The results support the use of AMBT to screen non-reactive aggregates and the CPT to confirm reactive aggregates. In addition, the application of reaction kinetics model on the AMBT expansion results further improves the accuracy of predicting potential ASR consistent with the CPT thus putting more credence to this short-term accelerated test method.

Keywords: Accelerated mortar bar test, alkali-silica reactivity, reaction kinetics, expansion rate, slowly reactive aggregate

1 INTRODUCTION

Standards Australia has published two new standard test methods to detect potential alkali-silica reactivity (ASR) in concrete aggregates:
AS 1141.60.1:2014 Potential alkali-silica reactivity - Accelerated mortar bar method (AMBT) and
AS 1141.60.2:2014 Potential alkali-silica reactivity - Concrete prism method (CPT).

During the development of the standards, three alternative AMBT methods namely the fixed flow in Roads and Maritime Services of New South Wales specifications (RMS T363), fixed water-to-cement ratio (ASTM C1260) and fixed free water-to-cement ratio (RILEM AAR-2) were considered. The committee agreed to adopt the ASTM C1260 fixed water-to-cement ratio method because of:
(1) more conservative mortar mix composition in ASTM C1260 compared to the fixed flow method (Shayan & Morris, 2001),
(2) reduced variability due to difficulty in determining the surface saturated dry condition (SSD) of crushed aggregates necessary in determining a fixed free water-to-cement ratio (Thomas, 2011), and
(3) reduced variability due to water adjustment for fixed flow (Davies and Oberholster, 1987),
The adoption of ASTM C1260 procedure also enables possible benchmarking of Australian test results to international research data (Stark, 1993, Touma, 2000 and Ideker *et al.*, 2012) and international proficiency program (Fournier *et al.*, 2012).

Thomas and Innis (1999) 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. These various attributes will be examined for the two new Australian test methods.

2. PERFORMANCE LIMITS

In both the AMBT and CPT methods, expansion limits after a particular period of immersion in NaOH solution or exposure period at 38ºC are used to indicate/classify the potential

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reactivity of aggregates tested. These expansion performance limits were derived from research and field experiences with the use of a wide range of aggregates.

Shayan and Morris (2001) compared accelerated mortar bar expansion of 18 aggregates of known service record, based on the RMS T363 and ASTM C1260, to find lower expansion of the RMS mortars than the corresponding ASTM mortars for reactive aggregates. This was 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 difference 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 1 below, 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 RMS limits were recommended for the interpretation of the adequacy of the amount of fly ash used in controlling the expansion.

TABLE 1 Roads and Maritime Services T363/A (RMS T363) - Aggregate Reactivity Classification.

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*	>> 0.10*	Reactive

*0.15% for naturally occurring fine aggregates

2.1 AS 1141.60.1 Accelerated Mortar Bar Test

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” behavior whereas 14-day expansions of more than 0.20% are indicative of “potentially deleterious” expansion. Aggregates with 14-day expansions between 0.10 and 0.20% are known to be innocuous and deleterious in filed 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 2: 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*-0.20%	Slowly reactive	< 0.10*%	0.10*% to <0.30%
Potential deleterious	≥ 0.20*%	Reactive	≥ 0.10*%	-
		Reactive	-	≥ 0.30%

*The value of the lower limit for natural fine aggregate is 0.15%

Shayan (2007) 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 RMS T363 correctly classified such aggregates as slowly-reactive aggregates.

The AS 1141.60.1 classified 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 0.3% to be a “slowly reactive” aggregate. Note that the lower limit applicable to natural sand is 0.15%. Table 2 compares the expansion limits of the two AMBT methods: AS1141.60.1 and ASTM C1260.

2.2 AS 1141.60.2 Concrete Prism Test

The ASTM C1293 tests the expansion of concrete 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 equivalent by mass of cement. Specimens are placed in a container stored in a 38.0±2°C. The non-mandatory 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 A23.2-27A-00 Table 1). It also suggests that it is reasonable to conclude that the amount of pozzolan or slag used in combination with an aggregate is the minimum needed to prevent excessive expansion in field concrete if the average expansion is less than 0.04% at two years (CSA A23.2-28A-02).

The 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 alkali content of 1.38% Na_2O equivalent.

For mitigation, the AS 1141.60.2 standard does not state any particular limit but refer to classification contained in the supply agreement.

3. CONSISTENCY OF AMBT & CPT CLASSIFICATION TO FIELD PERFORMANCE

The accuracy of test methods in predicting the likely reactivity of an aggregate is evaluated by examining the consistency of their classification with known field performance.

3.1 Accelerated Mortar Bar Test (AMBT)

ASTM C1260 AMBT expansion results of 32 aggregates with known field performance, reported by Stark et al. (1993) and Touma (2000), were assessed based on AS 1141.60.1 AMBT performance criteria as shown in Table 3. The results showed AS 1141.60.1 to improve the classification of reactive aggregates but underestimated non-reactive aggregates consistent with field structure or large blocks performance. The difference is due to a new classification of slowly reactive aggregates which include some field reactive and field non-reactive aggregates. An alternative method of classifying reactivity is therefore necessary.

AS 1141.60.1 is a step forward compared to ASTM C1260 as it attempts to classify an 'in-between' or 'uncertain' group of aggregates. The data also demonstrated the AS 1141.60.1 to be very conservative as it classified 28 aggregates to be slowly-reactive or reactive compared to only 24 found to be reactive in the field. Both ASTM C1260 and AS 1141.60.1 can be used to screen innocuous or non-reactive aggregates with ASTM C1260 shown to be a better screening test for innocuous aggregates.

Table 3: AMBT classification of alkali-silica reactive aggregates compared to field performance – International data.

Source of International data	*Field Reactivity*		*AMBT*					
			ASTM C1260			*AS1141.60.1*		
	Yes	*No*	*Reactive*	*Un-certain*	*Innocuous*	*Reactive*	*Slowly Reactive*	*Non-Reactive*
Stark, 1993	12	5	8	2	7	9	5	3
Touma, 2000	12	3	11	3	1	13	1	1
Total	24	8	19	5	8	22	6	4
Ideker, 2012	23	0	14	4	5	-	-	-

3.2 Concrete Prism Test (CPT)

Berube (1993), Touma (2000) and Ideker *et al.* (2012) published ASTM C1293 one year CPT expansion results totaling 62 aggregates with known field performance. The lower AS 1141.60.2 one year expansion limit of 0.03% led to a prediction of two more reactive aggregates than the corresponding ASTM C1293 limit of 0.04% as shown in Table 4. Overall, CPT predicts alkali-silica reactivity of aggregates more accurately than the AMBT.

The AMBT & CPT data by Touma (2000) and Ideker *et al.* (2012) also demonstrated the CPT to better predict field performance. The use of a lower expansion limit of 0.03% in AS 1141.60.2 did not improve aggregate classification compared to ASTM C1293.

Table 4: CPT Classification of alkali-silica reactive aggregates compared to field performance – International data.

Source of International data	*Field Reactivity*		*CPT*			
			ASTM C1293		*AS1141.60.1*	
	Yes	*No*	*Reactive*	*Non-Deleterious*	*Reactive*	*Non-Reactive*
Berube, 1993	6	18	6	18	7	17
Touma, 2000	12	3	12	3	12	3
Ideker, 2012	23	0	21	2	22	1
Total	41	21	39	23	41	21

3.3 Exceptions to the rules

Shayan (2007) experimented with concrete prisms and concrete blocks which showed the CPT to be ineffective in detecting the reactivity of some aggregates. The 300mm cube blocks of aggregates tested in Table 5 showed large expansion or map cracking usually after more than 1 year of exposure. Note that RMS T363 (AMBT) found the 3 reactive quartz gravels and the gneissic granite to be reactive.

TABLE 5: Summary of data from Shayan (2007).

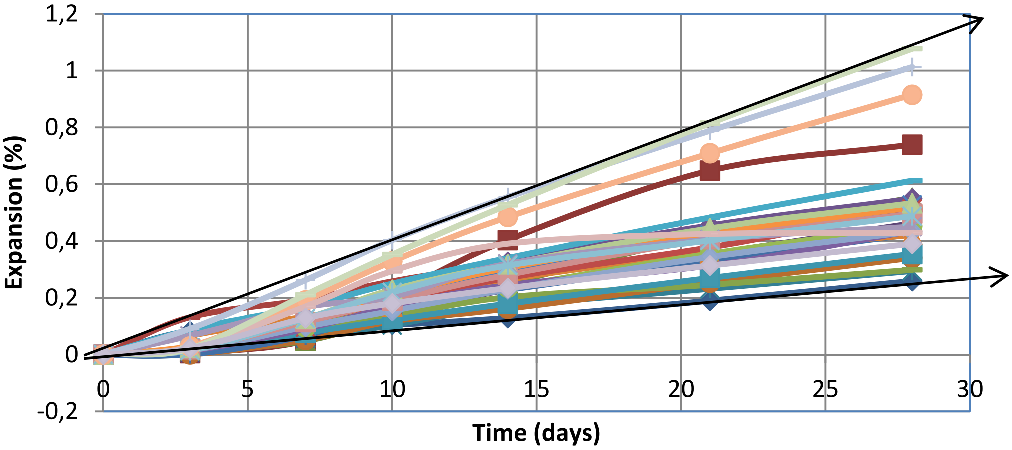
Structure	*Concrete Prism Expansion after 1 year*	*Note*
Australian Railway sleepers. Gneissic granite rocks which produced about 0.10% expansion at 21 days in the AMBT	Prism in 50ºC in water 0.06% with 1.4% alkali 0.09% with 1.9% alkali	300mm cube block in 50ºC water 0.12% with 1.4% alkali 0.18% with 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: PM, CC & KS.	PM just < 0.03% CC& KS well < 0.03% RMS T363 classified such aggregate as reactive.	Based on RMS T364 at high alkali 1.4% at cement content of 420kg/m$^{3.}$ PM 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 RMS T363.
Dam 3 phyllite aggregate UY	Prism 0.019% at 1 year Block 0.117% at 1 year	410kg/m^3 cement with 1.76% alkali

3.4 Hierarchy of test methods

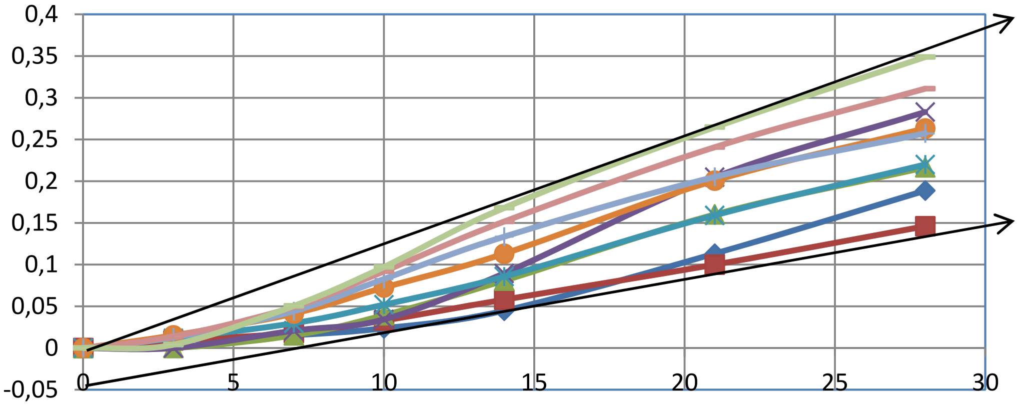
There has been no agreed hierarchy of the two Australian Standard test methods. However, it can be concluded from the application of the methods to international laboratory and field test data that the AS 1141.60.1 is a good screening test used in accepting non-reactive aggregate, whereas the AS 1141.60.2 is significantly more accurate in identifying potential reactive aggregates. This suggests a hierarchy of the two methods.

4. ALTERNATIVE AMBT PERFORMANCE CRITERION

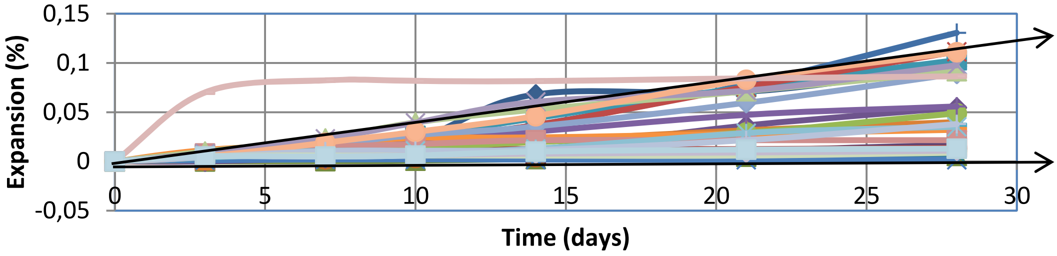
The traditional method of determining the reactivity of an aggregate by the Accelerated Mortar Bar Test (AMBT) is whether the expansion after a particular exposure period reaches an expansion limit. Alternative performance criteria are examined in this section to see if prediction can be made with improved certainty for a set of experimental data conducted for Cement Concrete and Aggregates Australia (CCAA).



1(c) Reactive: expansion rate 0.009-0.028 % per day



1 (b) Slowly-reactive: expansion rate 0.005-0.012 % per day



1 (a) Non-reactive: expansion rate 0-0.004 % per day

Figure 1 The range of expansion rates for non-reactive, slowly-reactive and reactive aggregates classified to AS 1141.60.1.

4.1 Expansion rate in classifying reactive aggregates

The criteria used in predicting the reactivity of aggregate were improved in AS 1141.60.1 from a single expansion limit to the expansion limits at two exposure periods of 10 days and 21 days.

This is fundamentally a criterion based on the 'expansion rate' over a period of 11 days.

Three sets of AMBT expansion characteristics of non-reactive, slowly-reactive and reactive aggregates are shown in Figures 1(a), 1(b) & 1(c) respectively. Their rate of expansion ranges are approximately:

Non-reactive 0-0.004 % per day,
Slowly reactive 0.005-0.012 % per day, and
Reactive 0.009-0.028 % per day

There is a range of expansion rate of 0.009-0.012 % per day where the slowly-reactive and potentially-reactive aggregates intercept. Such intercept post some difficulty in classifying reactivity of aggregate based exclusively on the AMBT expansion rate.

4.2 Reaction kinetic determined from AMBT expansion

An alternative method of classifying the reactivity of aggregate is by examining the reaction kinetics determined from the AMBT expansion result.

A study performed by Johnston *et al.* (2000) was conducted to determine an appropriate model to represent ASR expansion in the ASTM C1260 test. The Kolmogorov-Avrami-Mehl-Johnson (KAMJ) model which describes nucleation and growth transformation reaction kinetics was selected as potentially applicable and has the following form:

$$\alpha = 1 + \alpha_0 - e^{-k(t - t_0)^M} \qquad (1)$$

$$\alpha = \alpha_0 + (1 - \alpha_0)(1 - e^{-k(t - t_0)^M}) \qquad (2)$$

where:

α_0 is the degree of reaction at time t_0 when nucleation and growth become dominant, and
k is a rate constant which combines the effects of nucleation, multidimensional growth, the geometry of reaction products, and diffusion.

For expansion, α is the degree of reaction and α_∞ cannot exceed 1. Since the final expansion value for α is unknown, a formula proposed by Berliner et al. (1998) to model the kinetics of C_3S hydration was used.

For the study, ASTM C1260 tests were conducted using extremely reactive sand from South Dakota, and length measurements taken at 3, 7, 11, 14, 17, 21, 25, and 28 days with data being fit into the above equations. A value of three days was selected for t_0 with the corresponding expansion value used for α_0. The fit was determined with linear regression using:

$$\ln \ln \left(\frac{1}{1 + \alpha_0 - \alpha} \right) \text{ vs. } \ln (t - t_0) \qquad (3)$$

Equation 3 can be fitted to AMBT expansion values of individual aggregate to determine the kinetic parameters ln*k* and *M*. ln*k* is the abbreviation of natural log of Avrami Rate Constant *k*, and *M* is the Avrami Exponent. Johnston *et al.* (2000) determined the kinetic parameters of one set of aggregate reactivity data from CTL by Stark *et al.* (1993) and another South Dakota sands both showed a fairly clear demarcation between reactive and nonreactive aggregates of $\ln k_{14} < -6$ for nonreactive aggregates.

The kinetic parameters for the available AS 1141.60.1 AMBT expansions and the corresponding AS 1141.60.2 CPT reactivity classification from research conducted by the Cement Concrete and Aggregates Australia (CCAA) are tabulated in Table 6 and shown using different symbols in Figure 2.

It is clear that the $\ln k_{28} < -4.6$ criterion will give a clear demarcation between reactive and nonreactive aggregates classified by the CPT of all aggregates tested in the CCAA research program. There are three out of a total of 48 aggregates which were not correctly classified by this limit.

The use of a reaction kinetics limit ($\ln k_{28} < -4.6$), derived from the short-term accelerated mortar bar test, has been found to significantly improve the ability to predict the potential reactivity of aggregates consistent with the CPT classification. In Table 6, it can be seen that all aggregates, except Nos. 31, 35 and 45, are correctly classified by the reaction kinetic limit. This greatly improves the value of the short-term AMBT and makes it a more acceptable quality control test method.

TABLE 6: Rock type, AMBT & CPT Classification, Avrami Rate Constant k_{28} and Exponent M_{28} (CCAA).

	Rock type	**AS1141.60.1**	**AS1141.60.2**	**lnk_{28}**	**M_{28}**
1	Basalt	Non-reactive	Non-reactive	-10.43	1.71
2	Greenstone	Non-reactive	Non-reactive	-10.36	1.94
3	Basalt	Non-reactive	Non-reactive	-8.46	1.26
4	Latite (intermediate volcanic)	Non-reactive	Non-reactive	-8.05	1.59
5	Basalt (newer)	Non-reactive	Non-reactive	-7.90	0.85
6	Meta Quartzite	Non-reactive	Non-reactive	-7.44	1.73
7	Leucitic Basalt	Non-reactive	Non-reactive	-7.34	0.98
8	Olivine Basalt	Non-reactive	Non-reactive	-7.04	1.15
9	Micro-Granite	Non-reactive	Non-reactive	-6.81	1.44
10	Basalt (Greenstone)	Non-reactive	Non-reactive	-6.77	1.43
11	Hornfels	Non-reactive	Non-reactive	-6.69	1.10
12	Dolerite	Non-reactive	Non-reactive	-6.69	0.93
13	Olivine Basalt	Non-reactive	Non-reactive	-6.68	0.74
14	Olivine Basalt	Non-reactive	Non-reactive	-6.63	-0.30
15	Leucite Basalt	Non-reactive	Non-reactive	-6.19	1.00
16	Granite	Non-reactive	Non-reactive	-6.18	1.14
17	Granodiorite	Non-reactive	Non-reactive	-5.89	1.15
18	Basalt (Older)	Non-reactive	Non-reactive	-5.79	0.60
19	Basalt (glassy olivine)	Non-reactive	Non-reactive	-5.55	0.98
20	Basalt (newer)	Non-reactive	Non-reactive	-5.43	0.39
21	Olivine Basalt	Non-reactive	Non-reactive	-4.71	0.16
22	Pyroxene Andesite (basalt)	Slowly reactive	Non-reactive	-7.73	1.89
23	Basalt	Slowly reactive	Non-reactive	-6.23	1.61
24	Hornfels	Slowly reactive	Non-reactive	-6.23	1.53
25	Meta Quartzite	Slowly reactive	Non-reactive	-5.94	1.41
26	Meta Quartzite	Slowly reactive	Non-reactive	-5.41	1.31
27	Rhyolite	Slowly reactive	Non-reactive	-5.00	1.19
28	Round River Gravel	Slowly reactive	Non-reactive	-4.99	1.25
29	Meta Quartzite	Slowly reactive	Non-reactive	-4.67	1.20
30	Granodiorite	Reactive	Non-reactive	-6.69	1.55
31	Greenstone	Reactive	Potentially reactive	-5.32	1.62
32	Pyroxene Andesite	Reactive	Non-reactive	-5.29	1.82
33	CRG	Reactive	Non-reactive	-4.61	1.30
34	Meta Quartzite	Reactive	Potentially reactive	-4.51	1.08
35	Biotite Schist	Reactive	Non-reactive	-4.36	1.09
36	Rhyodacitic Tuff	Reactive	Potentially reactive	-4.17	1.07
37	Hornfels	Reactive	Potentially reactive	-4.05	1.09
38	Meta Siltstone & Meta Pelite	Reactive	Potentially reactive	-4.02	1.08
39	Meta Greywacke	Reactive	Potentially reactive	-3.98	1.15
40	Schist	Reactive	Potentially reactive	-3.98	1.12
41	Rhyodacitic Porphyry	Reactive	Potentially reactive	-3.86	1.14
42	Hornfels	Reactive	Potentially reactive	-3.82	1.00
43	Rhyodacite	Reactive	Potentially reactive	-3.69	1.04
44	Quartzitic Latite	Reactive	Potentially reactive	-3.68	1.02
45	Basalt (partly glassy)	Reactive	Non-reactive	-3.62	1.33
46	Rhyodacitic Porphyry	Reactive	Potentially reactive	-3.52	1.01
47	Meta Siltstone	Reactive	Potentially reactive	-3.29	0.90
48	Basalt	Reactive	Potentially reactive	-3.25	0.76

Note: ln k_{28} is natural log of Avrami Rate Constant k_{28} from 3 to 28 days, and
M_{28} is the Avrami Exponent from 3 to 28 days.

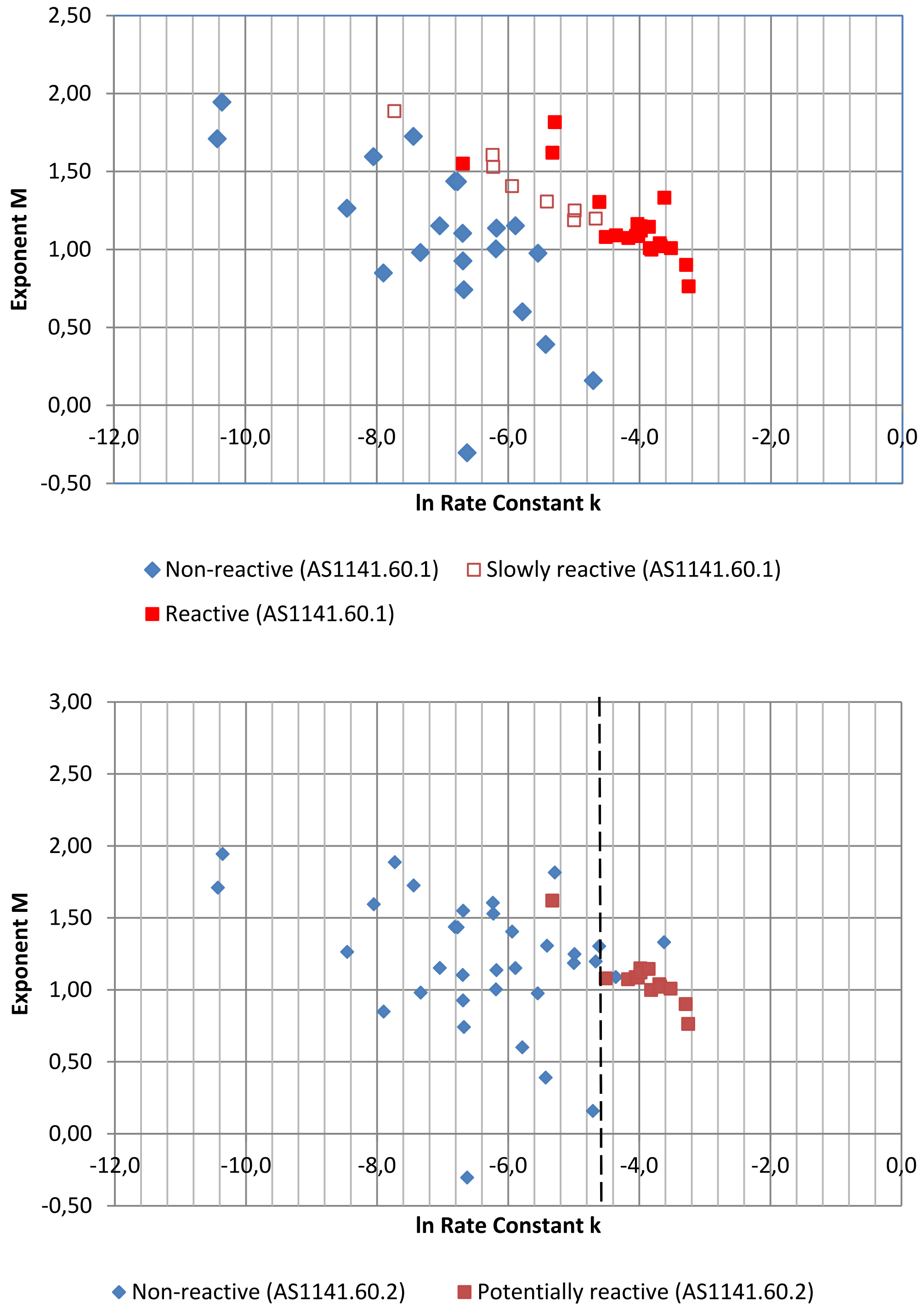


Figure 2 28-day Avrami exponent versus rate constant: CCAA AMBT data.

5. RESULTS & DISCUSSION

Based on the international database, the Australian Standard AS 1141.60.1 has been shown to correctly screen 4 out of 8 (50%) of field non-reactive aggregates and 22 out of 24 (92%) field reactive aggregates. It also predicts six slowly-reactive aggregates out of which only two (33%) were confirmed reactive in the field. Both AS1141.60.2 and ASTM C1293 accurately identifies (over 95%) reactive aggregates consistent with field performance of 62 aggregates reported in international database. This confirms the hierarchy of the CPT over the AMBT for considerable large number of aggregates.

The short and practical 28-day testing time frame in the Australian AMBT warranted an examination of alternative performance criterion to improve the consistency of classification of aggregates to the CPT classification. The evaluation of the reaction kinetics, based on AMBT expansion rate from 3 to 28 day, has been found effective by the use of the natural log of Avrami Rate Constant k_{28}, $\ln k_{28} < -4.6$, to correctly delineate 32 CPT-nonreactive and 13 CPT-reactive aggregates. Three from 48 aggregates were wrongly classified.

6. CONCLUSIONS

The Australian Standard AS 1141.60.1 has been shown to be a good screening test for non-reactive aggregate whereas AS1141.60.2 accurately identifies most reactive aggregates consistent with field performance. There have been few exceptions to this rule. A reaction kinetics parameter, the natural log of Avrami Rate Constant k_{28}, has been found to effectively delineate CPT-nonreactive aggregates from CPT-reactive aggregates with some exceptions. The reaction kinetics nevertheless greatly improved the classification of reactivity consistent with CPT classification.

The adoption of ASTM C1260 and ASTM C1293 test procedures in the corresponding Australian Standards AS1141.60.1 and AS1141.60.2 enabled benchmarking of Australian test results to Australian and international research data (Shayan, 2007, Stark *et al.*, 1993, Touma, 2000 and Ideker *et al.*, 2012) and international proficiency program (Fournier *et al.*, 2012). The two Australian Standards and their performance criteria, and in particular the AS 1141.60.1, satisfied all important attributes of test methods on the basis of the ease of testing, the time taken to complete the test, the precision of the outcomes and ultimately the ability of the test to predict field performance.

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