Application of AMBT to the Assessment of SCM Blended Cements in ASR Mitigation

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Abstract: Alkali-silica reaction (ASR) is a cause of durability issues in concrete resulting in cracking and loss of serviceability in concrete structures. The risk of ASR is related to aggregate reactivity which can be assessed using the accelerated mortar bar test, AMBT (AS1141.60.1), and the concrete prism test, CPT (AS1141.60.2). Non-reactive aggregates may not always be available and hence mitigation strategies are required. Currently, however, there are no standard test methods in Australia for assessing mitigation strategies for risk of damage caused by ASR. This paper investigates the potential of AMBT in the assessment of reactive aggregate-binder combination in mitigation strategies and presents the outcome of an AMBT investigation into the ASR reactivity of a reactive aggregate using supplementary cementitious materials (SCMs) in blended cements.

Keywords: ASR, AMBT, alkali concentration, SCM, fly ash, GGBFS

1. INTRODUCTION

The alkali-silica reaction (ASR) is a deleterious reaction between alkali hydroxides and reactive silica in concrete resulting in the precipitation of an alkali-silica gel which causes expansion and, potentially, cracking of the concrete [1]. As such, ASR can be a serious problem in infrastructure durability. For ASR to occur, the three reaction components necessary are:

- available alkali in the pore solution,
- reactive silica, and,
- moisture.

The reaction proceeds through the dissolution of the reactive silica present in the aggregate followed by the precipitation of the ASR gel incorporating calcium and alkali ions from the pore solution [1, 2]. This results in the precipitation of an expansive alkali-silica gel, the ASR gel, which then exerts mechanical stress on the concrete leading to cracking of the concrete.

In order to reduce the potential for deleterious ASR, a number of mitigation strategies are employed including:

- the use of non-ASR reactive aggregates,
- limitations on the available alkali in the concrete mix (< 0.6% Na_2O_e in cement, < 2.8 kg/m^3 in concrete),
- incorporation of supplementary cementitious materials (SCMs)

or a combination of these strategies. Strategies for minimising the risk of ASR are outlined in SA HB 79:2015 [3] which provides guidance on the screening of aggregates based on petrographic analysis (AS 1141.65 – withdrawn 2019 [4]), accelerated mortar bar test AS1141.60.1 (AMBT) [5] and the concrete prism test AS1141.60.2 (CPT) [6]. The expansion tests have been reviewed and have been found to perform reliability with respect to published field performance when the Australian standard expansion limits are observed [7]. The petrographic analysis test, AS1141.65, on the other hand, has been withdrawn. As it is part of HB 79 for assessing aggregate reactivity, the handbook should be revised to accommodate this change.

HB 79 also provides guidance on using mitigation strategies using supplementary cementitious materials (SCMs) as well as limiting the available alkali. However, there is currently no standard in Australia for assessing binder systems. Expansion tests have shown potential for assessing the capacity of SCMs to mitigate ASR [8,9]. Additionally, performance based methods for assessing cementitious materials are available outside Australia e.g. ASTM C1778-23 [10].

This paper focuses on the AMBT as it is a rapid screening method. The AMBT is applied to assessing the mitigation potential of two SCMs: fly ash (FA) and ground granulated blast furnace slag (GGBFS) using a

Table 1. Reactivity classification for the AMBT as defined by AS1141.60.1.

Mean mortar bar expansion %		AS 1141.60.1 aggregate reactivity classification
Duration of specimens in 1M NaOH 80 °C		
10 days	21 days	
---	E<0.10*	Non-reactive
E<10*	0.10≤E<0.30	Slowly reactive
E≥0.10*	---	Reactive
---	0.30≤	Reactive

* The value for natural fine aggregates is 0.15%.

reactive natural sand as the reactive aggregate. The influence of alkali concentration is also investigated by varying the immersion bath solution concentration to assess its role on ASR reactivity. For the AMBT, the categorisation of aggregate reactivity in AS1141.60.1 is based on expansion limits at 10 and 21 days as outlined in Table 1. As the categorisation of reactivity is based on these expansion limits under standard testing condition, this paper uses these limits but assesses the efficacy of SCMs in mitigating ASR and the role of alkali concentration in the reaction by determining the time taken to reach the 0.1% and 0.3% expansion limits. The relative times to reach these limits will be used to provide an indication of the potential of the AMBT for assessing SCMs and alkali concentration in mitigation strategies.

2. MATERIALS AND METHODS

2.1 Mortar Prisms

A natural river sand classified as reactive by AS1141.60.1 was selected for mortar bar preparation. The reactive river sand contains 10.7% moderately strained quartz, 2% heavily-strained quartz and 1.3% finely microcrystalline quartz within fragments of indurated meta-greywacke/siltstone and acid volcanic rock.

The cementitious materials used were a standard type GP cement (Na_2O_e = 0.47%), FA and GGBFS. For the blended cements, the cement was replaced with 25% FA and 65% GGBFS by weight based on the recommendations in SA HB 79: 2015 [3].

Mortar bars were prepared using the procedure outlined in AS1141.60.1. Gauge studs were placed within the mould prior to mixing and calibrated to have a gauge length of 250 mm. Fine aggregate was prepared in its natural unaltered grading by oven drying at 110°C before cooling for mixing. Potable tap water was used for mixing. The mortar prisms were cured in three gang moulds for 24 hours before demoulding and immersing in tap water at room temperature before heating to 80°C for 24 hours for equilibration prior to zero day length measurement and subsequent immersion in alkali baths equilibrated at 80°C.

2.2 Immersion Baths

Four immersion baths were used. The immersion bath solution concentrations consisted of sodium hydroxide (NaOH) solutions at 0.4, 0.7 and 1M and a bath of saturated lime water (calcium hydroxide, $Ca(OH)_2$). Distilled water was used to prepare these solutions. The 0.4M NaOH immersion bath was selected as the lowest alkali solution concentration used as this was the determined pore solution concentration for the cement [11]. During immersion, the baths were kept heated at 80°C throughout the duration of the test. Mortar bars were vertically oriented within each bath, supported by a stainless steel grid so that no contact with the gauge pins occurred.

2.3 Expansion Measurements

Expansion measurements were carried out on a steel frame comparator equipped with a Mitutoyo digital micrometre referenced to a 295 mm invar reference bar. Length measurements were recorded at Day 0 (immediately after removal from 80°C water bath) and then periodically up to 213 days.

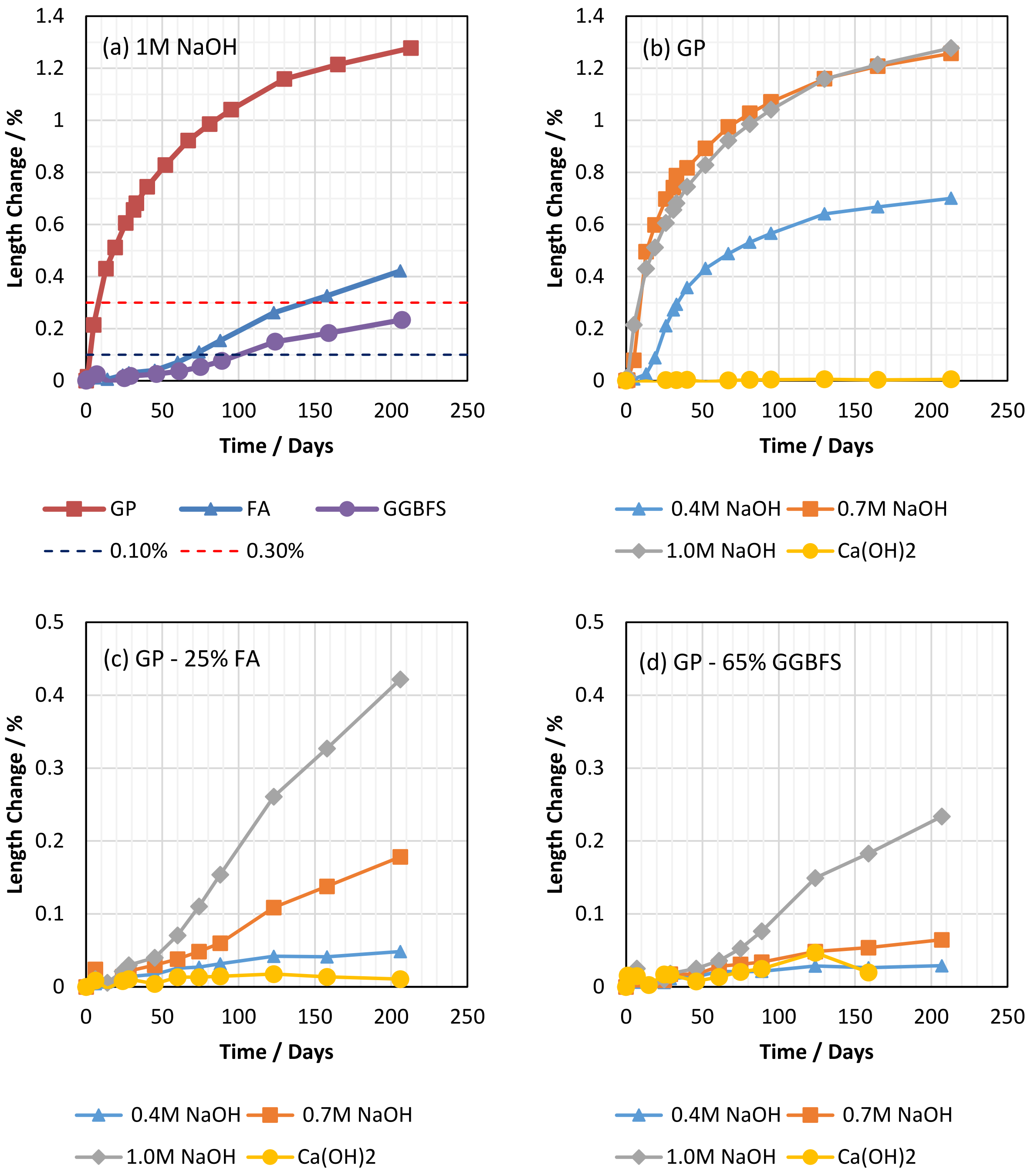

Figure 1. AMBT expansion measurements for mortar bars containing a reactive river sand: (a) 1.0 M NaOH solution for GP, 25% FA and 65% GGBFS, and as a function of immersion bath concentration for (b) GP cement, (c) 25% FA and (d) 65% GGBFS.

3. RESULTS

Expansion results for each mix in each immersion bath are reported in Figure 1. Table 2 lists the interpolated times required to reach the two expansion limits, 0.1% and 0.3%, as outlined in Table 1. Note that 0.1% has been selected as the reference expansion rather than 0.15% prescribed by AS1141.60.1 for natural sands as the aim of this study is to investigate binder systems and alkali concentration and, hence, the more conservative 10 day expansion limit is applied. Also note that in Table 2, if the expansion limit was not

Table 2. Interpolated time in days taken to reach 0.1% and 0.3% expansion (selected based on the AS1141.60.1 expansion thresholds (Table 1)). A dash ('-') is used where the limit was not reached withing the timeframe of the experiment.

	Time to 0.1% Expansion / Days				Time to 0.3% Expansion / Days		
	GP	FA	GGBFS		GP	FA	GGBFS
$Ca(OH)_2$	-	-	-		-	-	-
0.4M NaOH	20	-	-		34	-	-
0.7M NaOH	5	117	-		9	-	-
1.0M NaOH	3	70	100		8	144	-

reached in the 213 day timeframe of the experiment, a dash ('-') has been used. No expansion was observed for any of the mortar bars immersed in lime water.

Figure 1(a) shows the expansion for the three binder systems immersed in 1M NaOH at 80°C. Using the AMBT expansion limits listed in Table 1, the natural river sand aggregate is shown to be reactive. For the GP cement system (standard testing conditions) the time taken to reach 0.1% expansion was 3 days and only 8 days to reach 0.3% expansion. These times demonstrate that the aggregate is highly reactive (note that 'highly' is not a categorisation used in AS 1141.60.1). The use of SCMs reduces this rate of reaction significantly with 25% FA blended cement taking 70 days and GGBFS blended cement taking 100 days to reach 0.1% expansion, more than 20 times the time for the pure GP cement mortar bars. For the 0.3% expansion limit, the FA blended cement took 144 days to reach the limit, 18 times longer than for the GP cement mortars, while the GGBFS blended cement mortar bars did not reach the 0.3% limit in the 213 day timeframe of the test.

Figure 1(b) shows the expansion of the GP cement mortars as a function of the NaOH concentration. The 0.7M and 1.0M solutions produce similar expansion profiles which suggests that the reactive natural river sand aggregate shows pessimum ASR reactivity where increasing the bath reactivity (i.e. NaOH concentration) does not increase the degree of expansion. Reducing the alkali concentration to 0.4M, however, results in significant reduction in the expansion as would be expected by reducing the reactivity of the bath. Eliminating alkali ions from the bath by immersing in saturated lime water results in zero expansion demonstrating the necessity of alkali ions in ASR.

Inspecting the time taken to reach the AMBT expansion limits in Table 2 for the GP cement mortars, both 0.7 and 1.0M NaOH conform to reactive categorisation. Reducing the alkali content to 0.7M has not had much effect on the rate of expansion indicating pessimum behaviour. Reducing the alkali concentration to 0.4M reduces expansion. In this case, the reactivity has reduced to a slowly reactive classification. Removing the alkali by using lime water results in no expansion. These expansion results indicate that there is a potential for an alkali threshold.

The expansion for the blended cement mortars as a function of the immersion bath concentration are shown in Figures 1(c) and (d). The expansion is significantly lower for both FA and GGBFS blended cements than for the GP mortars over the timeframe of the test. The expansion diminishes significantly with reducing alkali concentration demonstrating the effect of alkali concentration on the rate of reaction. Immersion in lime water also resulted in zero expansion.

The FA blended cement showed greater expansion than the GGBFS blended cement. This difference may be associated with the relative degree of substitution of the SCM as well as relative effectiveness in mitigation for FA and GGBFS. As the mortar bars were all subject to the same concentration solutions, and, hence, the same availability of alkali, alkali content in itself is not ascribed to the differences in expansion.

For the blended cements, expansion to 0.1% was observed for the 0.7M and 1.0M immersion baths, but not for the 0.4M bath in the timeframe of the tests. 0.3% expansion was observed only for the FA blended cement for the 1.0M bath. Additionally, expansion to either of these thresholds was at least more than 3 times the 21 day limit at 0.1% expansion (70 days to reach 0.1% for the 1.0M, FA blend). The absence of expansion at long immersion times demonstrates the potential for AMBT as a screening aid for mitigation strategies when testing binders for their potential to minimise the risk of ASR when using a reactive aggregate as indicated in HB 79 [3]. The fact that expansion is observed for the SCM blends is related to the reactivity of the test, but potentially suggests that SCMs have an inhibiting effect rather than a mitigation effect as, for the lime water solution where there is an absence of alkali ions, the reactive aggregate shows no propensity to ASR expansion.

4. DISCUSSION

This study has investigated the expansion of mortar bars containing a reactive aggregate as a function of the binder and the alkali content of the solution. Both of these approaches are noted strategies for mitigating the risk of ASR [1, 12-13]. SCMs incorporated in blended cements have been shown to be effective in mitigating ASR as well as over long durations in field tests [7, 8]. Similarly, limiting the alkali concentration in the pore solution has been shown to be effective in limiting the risk of ASR [14]. Reducing the alkali content of the solution results in a lower reactivity environment and, hence, reduced expansion [14, 15].

A reduction in expansion is expected to occur with reducing alkali concentration. The reactive natural sand investigated, however, showed pessimum behaviour where the expansion for 0.7M and 1.0M were similar. Similar observations have been observed for immersion in pore solution tests [11]. HB 79 guidelines suggest using the pessimum content for an aggregate when investigating blended cement binders in mitigation [3]. In this study, the pessimum behaviour is inferred based on expansion as a function of alkali concentration. Alkali concentration in AMBT is, therefore, an alternative way of identifying pessimum behaviour, if not pessimum the content of the reactive aggregate directly.

In order to demonstrate the role of alkali in ASR, saturated lime water, an alkaline, but alkali free immersion solution, was investigated and resulted in zero expansion for the GP mortar bars. The zero expansion observed for GP mortar bars immersed in lime water demonstrates that removing alkali from the reaction inhibits ASR. An alkali pore solution threshold concentration of 0.3 to 0.4M has been recently proposed for the initiation of expansion due to ASR [14]. This study did not directly investigate alkali thresholds, as the lower limit of the alkali solution concentration was 0.4M based on previously reported pore solution concentrations measured for the cement used [11]. This lowest concentration is at the top end of the proposed pore solution alkali concentration threshold and the GP mortar bars immersed in the 0.4M bath showed expansion above 0.1% at 20 days which is within the 21 day limit (Table 1) thus demonstrating aggregate reactivity and the aggregate would be classified as slowly reactive if the standard AMBT expansion limits are applied. This correlation with the high end of the 0.3 to 0.4 M estimated alkali pore solution concentration threshold suggests that AMBT could be applied to binder-aggregate alkali pore solution threshold concentration determination in ASR mitigation. Similar results for expansion in AMBT have been reported for expansion of mortar bars immersed in bath solutions below and above this threshold range at 80°C [15].

Partial substitution with SCM results in significant reduction in the degree of expansion. No measurable expansion is observed at 0.4M suggesting that the pore solution in the mortar bars is reduced to below to the threshold required for deleterious expansion [15]. Incorporation of alkali in the CSH formed by the pozzolanic reaction with the SCM is the likely origin of the reduction in pore solution alkali concentration coupled with pore blocking limiting access of the external alkali solution [14]. As the bath concentration increased, expansion rate increased, but the rate of expansion remained low for both the 0.7 and the 1.0M immersion baths. Expansion to 0.1% was observed after more than 70 days for the 1.0M bath indicating a significant degree of mitigation.

The immersion solution in AMBT produces a nominally limitless supply of alkali for ASR. For the blended cement mortar bars, the expansion that is continued to be observed may reflect this limitless supply of alkali and may indicate that the SCMs act as inhibitors to ASR and have a finite capacity to mitigate ASR. If this is the case then the SCMs act in inhibition of ASR rather than in mitigation (although inhibition may be beyond the design life of the material). These tests are, however, carried out in an extremely reactive environment. As such the AMBT is extremely conservative in assessing ASR aggregate reactivity [2]. The significant reduction in expansion for the blended cements suggests that the AMBT can reliably be used to assess reactive aggregate binder combinations for their susceptibility to ASR.

5. CONCLUSIONS

The AMBT has shown that the expansion of mortar bars is alkali concentration dependent and although this study did not investigate a threshold for alkali concentration for ASR expansion, the lack of expansion in the absence of alkali (lime saturated water immersion bath) demonstrated the potential for AMBT in the assessment of a pore solution alkali concentration threshold determination for reactive aggregates.

The observation that maximum expansion was observed for both the 0.7M and 1.0M NaOH indicated that the AMBT can be used in aggregate pessimum behaviour assessment if not directly the determination of aggregate pessimum content.

The reduced expansion of mortar bars containing a reactive natural aggregate when using blended cements demonstrates the potential of AMBT as a method of identifying blended cement binder-reactive aggregate combinations for ASR mitigation.

Currently there are no standard test methods in Australia for assessing mitigation strategies for risk of damage caused by ASR. This study, along with many comparable studies, has demonstrated the potential of AMBT in the assessment of mitigation strategies for reactive aggregate-binder combinations using SCMs in blended cements. It has also demonstrated that the AMBT has the potential to aid the assessment of alkali thresholds for reactive aggregates.

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