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The ability of SCMs to mitigate ASR in cements of higher alkali contents assessed by pore solution method

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Abstract

This study reports on the efficacy of supplementary cementitious materials (SCMs) to mitigate ASR when used in conjunction with cement of higher alkali contents (up to 1%Na_2O_{eq}). The expansion of concrete prisms immersed in simulated pore solution was studied in order to address the limitations of conventional ASR testing methods AMBT and CPT. The alkali concentration in the simulated pore solution was derived from the 28-day age pore solution of pastes with equivalent composition as the concrete binder of interest. The concrete prisms were prepared using Australian sourced materials: 2 types of reactive aggregates (dacite and rhyolite), 2 types of SCMs (fly ash and slag) and cement with 0.6% Na_2O_{eq} original alkali content that was boosted with alkali to obtain 1.0% Na_2O_{eq}. The concrete prisms were stored at 38 °C and at 60 °C. Expansion results show that 25% fly ash and 50% slag are both sufficient to mitigate ASR even with cements with alkali content up to 1.0%Na_2O_{eq}. Extensive amount of ASR products were observed in concretes without SCMs. Small amount of ASR products were also observed in concrete with SCMs, even if there was no notable expansion observed.

***Keywords**: alkali; mitigation; fly ash; pore solution; slag*

1. INTRODUCTION

The first case of alkali-silica reaction (ASR) in Australia is that of a bridge structure in Causeway, Perth. The bridge has been identified to be suffering from ASR in 1983 and this was reported during the 7th ICAAR conference held in 1986 [1]. Since then, several other structures all over Australia have been reported to be suffering from ASR. SA HB 79:2015 "Alkali Aggregate Reaction—Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia" lists some of the structures affected by ASR.

Australian strategies to mitigate ASR involve both the use of SCMs and limiting the alkali content of the cement. SA HB 79:2015 provides recommended levels of SCM replacement to mitigate ASR as follows: 10% silica fume, 15% metakaolin, 25% for fly ash and 50-65% for slag. For practical applications (commercial), typically only fly ash and slag are used. The use of metakaolin and silica fume is limited for reasons of cost. Shayan et al. have reported on the effectivity of Australian fly ash and slag at 25% and 50% replacements respectively in mitigating ASR [2, 3].

In conjunction with the use of SCMs, Australian standards also impose a strict limit of 2.8 kg/m^3 of alkali in concrete leading to the limitation of 0.6% Na_2O_{eq} (sodium oxide equivalent=Na_2O + 0.658 K_2O) in the cement in order to mitigate ASR. This low cement alkali limit results in tremendous amount of raw materials (limestone in particular) deemed to be unsuitable for cement production. Since the ability of SCMs to mitigate ASR has long been established, both by accelerated test methods and field exposure studies [4-7], there is a question as to whether a strict cement alkali limit is still necessary when SCMs are incorporated in the concrete mix. Relaxing the cement alkali limit offers potential not only to reduce costs associated with cement production but also conserve environmental resources.

Standard laboratory test methods such as the accelerated mortar bar test (AMBT) and the concrete prism test (CPT) are typically employed to assess aggregate reactivity and SCM efficacy in the short term [8]. For testing reactivity of aggregates, Australia uses its own version of these accelerated tests, AS 1141.60.1 (AMBT) and AS 1141.60.2 (CPT) which are very similar to well-known ASTM C1260 and ASTM C1293, respectively with the exception of the performance limits [5]. Australia, to date, however has no dedicated standard for assessing SCM efficacy in ASR mitigation and thus, AS 1141.60.1 and AS 1141.60.2 are typically extended for this purpose. Sirivivatnanon et al. have reported on the reliability of extending the Australian test methods for assessing ASR mitigation [9].

Despite worldwide popularity of the accelerated test methods, with several countries having their own version of the tests, AMBT and CPT are both questionable with respect to their ability to assess the effect of cement alkalinity on ASR expansion [8, 10]. In the AMBT there is an inexhaustible supply of alkalis from the storage solution of 1M NaOH and high temperature of 80 °C. As a consequence, this test has been shown incapable of detecting expansion differences in mortars of varying cement alkali contents [11]. CPT, which is generally accepted as the more reliable test method due to the lower temperature of 38 °C and fixed supply of alkali, is prone to alkali leaching [8, 12, 13]. This results in an underestimation of expansion and consequently may indicate lower dosage of SCMs than required for effective mitigation in the field [8, 14, 15]. Field studies, which are considered to be the most reliable, take very long time and require not only commitment but also abundant resources. For this reason, most countries, including Australia, do not have field exposure sites at present.

Due to the limitations of existing ASR test methods, this study uses an alternative method to assess the effect of cement alkalinity on the ability of SCMs to mitigate ASR. The test method, developed by the Laboratory of Construction Materials (LMC) at EPFL [16], makes use of simulated pore solutions to assess the efficacy of SCMs in mitigating ASR by addressing the leaching issues in CPT and eliminating aggressive test conditions in AMBT (high temperature and excessive supply of alkalis). By studying the expansion of highly reactive aggregates in combination with SCMs (fly ash and slag) using the simulated pore solution method, the aim of this study is to determine if the SCMs at recommended dosages will work to mitigate ASR when used in conjunction with cement which has effective equivalent alkali content up to 1.0% Na_2O_{eq}.

2. MATERIALS AND METHODOLOGY

2.1 Raw materials

All raw materials (cement, aggregates, SCMs) were sourced in Australia and comply with Australian standards AS 3972 (General Purpose and Blended Cements), AS 3582.1 (Supplementary Cementitious Materials: Fly Ash) and AS 3582.2 (Supplementary Cementitious Materials: Slag-Ground Granulated Blast Furnace). Table 2.1 lists the X-ray fluorescence (XRF) oxide composition of all the raw materials.

Table 2.1: XRF oxide composition of the raw materials

Oxide wt%	GP Cement	Fly Ash	Slag	Dacite Aggregate	Rhyolite Aggregate
SiO_2	19.67	59.21	34.12	68.38	61.93
TiO_2	0.22	1.11	0.87	0.36	0.81
Al_2O_3	4.78	28.11	14.37	13.25	15.44
Fe_2O_3	3.10	3.68	0.30	3.32	5.75
Mn_3O_4	0.12	0.11	0.36	0.06	0.10
MgO	0.91	0.53	5.31	1.30	1.57
CaO	64.18	2.48	41.59	2.35	2.30
Na_2O	0.33	0.63	0.35	2.41	5.65
K_2O	0.41	1.18	0.26	3.84	2.89
P_2O_5	0.06	0.41	0.01	0.08	0.18
SO_3	2.37	0.16	2.83	<0.01	0.07
L.O.I.	4.09	1.05	0.35	4.52	4.09

2.2 Preparation of concrete prisms and ASR expansion measurement

Concrete prisms (70 x 70 x 280 mm) with cement content of 410 kg/m^3 were cast using Australian reactive aggregates, SCMs and a GP cement. Three concrete prisms were prepared for each mix using the same type of aggregate for both fine and coarse component (0.16 µm- 22.4 mm aggregate sizes) keeping the water to cement ratio at 0.46 for all mixes. To simulate a cement with 1.0% Na_2O_{eq} alkali content, the cement with original 0.6% Na_2O_{eq} was boosted with 0.4% extra alkali by adding sodium hydroxide (NaOH) to the mixing water. The alkali was added based on the cement content and not the binder content. The SCMs were used at Australian recommended dosages for effective mitigation, 25% for fly ash and 50% for slag. The concrete prisms were demoulded after 24±2 hours and left to cure for 28 days in a high humidity environment (fog room), at 20±2 °C before being stored in simulated pore solution at 38 °C and 60 °C. Initial measurements were obtained using a vertical comparator before immersing the concrete prisms in the storage solution (zero hour expansion reference). The ASR expansion measurements were obtained every 28 days thereafter to monitor expansion. For expansion measurements, the concrete prisms were taken out of the climate chamber 1 day prior measurement to cool to room temperature as this ensures that the concretes are in similar conditions and therefore reduce measurement errors.

The simulated pore solution used to store the concrete prisms was prepared by reproducing the alkali content (Na and K concentration) of the expressed pore solution from the paste system corresponding to the binder of the concrete at 28 days. Pore solution was extracted from the pastes at 28 days using a compression testing machine and analyzed using ICP-OES.

2.3 Characterization of the ASR products

At 6 months (168 days), part of the concrete specimens were sectioned and polished for microstructural analysis. The polished specimens were carbon coated to prevent charging during SEM imaging. Imaging was carried out using FEI Quanta 200.

3. RESULTS AND DISCUSSION

Figures 3.1 and 3.2 show the expansion data up to 12 months for the concrete prisms immersed in simulated pore solution at 38 °C and 60 °C respectively. Whereas, the prisms with no SCMs have expanded considerably (both aggregates), the prisms with SCMs (25% fly ash or 50% slag) even with cement boosted with 0.4% alkali (1% effective Na_2O_{eq}), do not show significant expansion. The concrete prisms stored at 60 °C notably exhibits earlier onset of expansion as well as higher degree of expansion at 12 months compared to the 38 °C concrete prisms. Regardless of the storage temperature, the expansion results demonstrate that the SCMs can potentially mitigate ASR even with cements of higher alkali contents. More time is however needed for monitoring the expansion particularly of the 38 °C concrete prisms. The extended period may be required as there is no acceleration of potential alkali-silica reaction as alkali was not raised to 1.25% as done in the traditional concrete prism test.

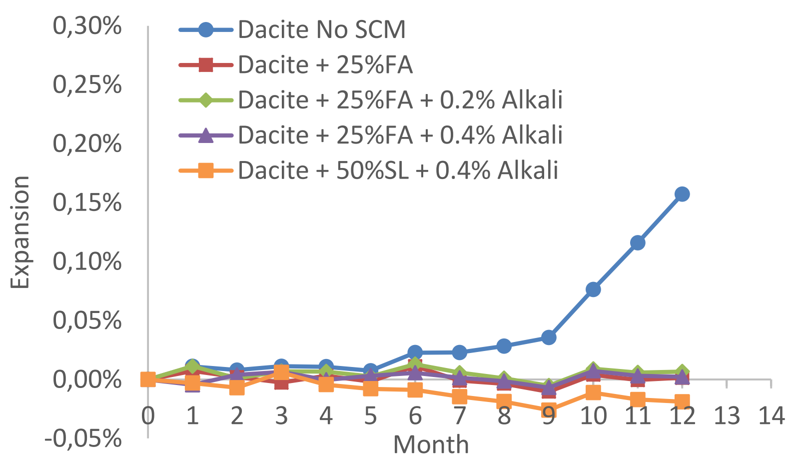

Figure 3.1: Measured expansion of dacite concrete specimens stored at 38 °C

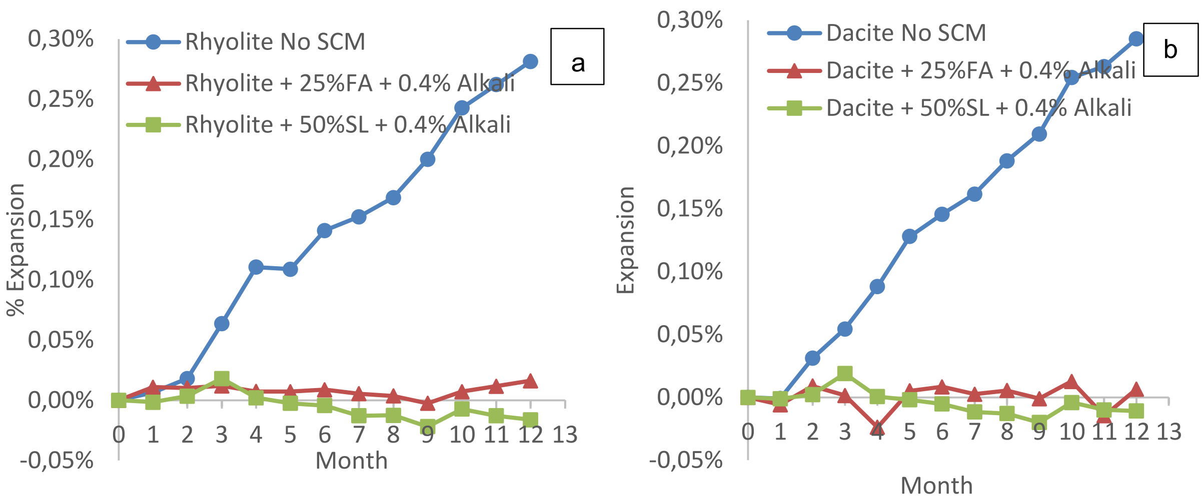

Figure 3.2: Measured expansion of a) rhyolite and b) dacite concrete specimens stored at 60 °C

The concrete specimens stored at 60 °C were sectioned to analyse the ASR products. Extensive amount of ASR gel was observed in concrete specimens with no SCMs. The appearance and location of the gel (Figure 3.3a) are consistent with that reported in literature [17, 18]. In the concrete with SCMs it was also possible to find, very occasionally, deposits of gel despite having no significant expansion (Figure 3.3b). The ASR products observed in the concrete with SCMs have thicknesses typically of maximum 5 μm in contrast to the veins of about 20 μm in concrete with no SCMs.

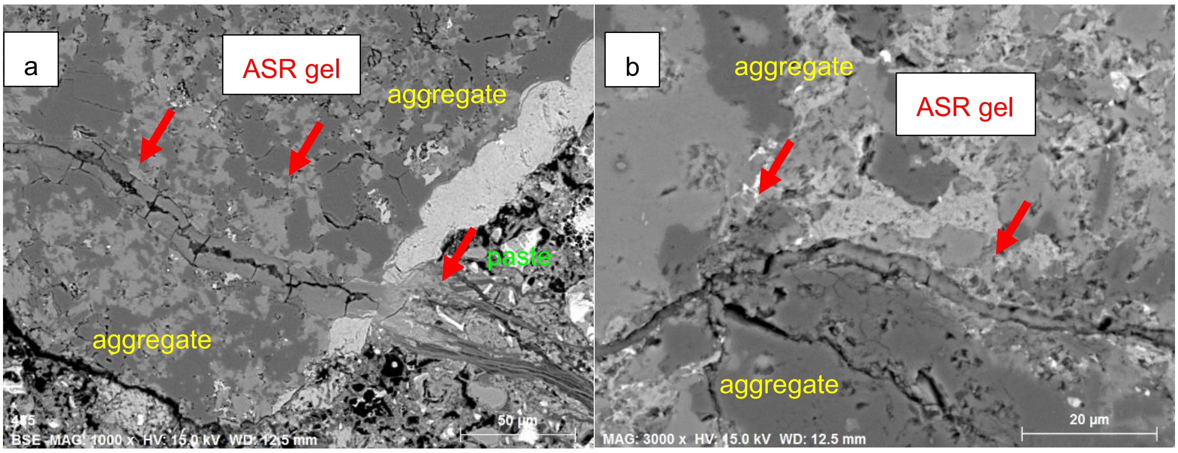

Figure 3.3: Representative BSE SEM images of the ASR gel found in rhyolite concrete stored at 60 °C a) without SCM and b) with 25%FA+0.4% alkali

4. CONCLUSIONS

This study investigated the efficacy of Australian SCMs to mitigate ASR when the effective cement alkali content was raised to 1.0% Na_2O_{eq} from original alkali content of 0.6% Na_2O_{eq}. To avoid excessive alkali associated with AMBT, and leaching in CPT, simulated pore solution prepared based on the pore solution alkali concentration at 28 days was used as storage solution.

The expansion results show that while the concrete without SCM has significant expansion after 12 months for both storage temperatures 38 °C and 60 °C, the concrete mixes with SCMs (either 25% fly ash or 50% slag) has no expansion up to 12 months. Results therefore suggest that the SCM dosages used are sufficient to mitigate ASR even at higher cement alkali contents. Moreover, the results also demonstrate that the simulated pore solution method is a viable alternative ASR testing method.

The concretes stored at 60 °C were sectioned at 6 months in order to characterize the ASR products. ASR products were observed in extensive quantity in the concrete without SCM. The concrete with

SCMs, although did not manifest expansion also showed the presence of small amounts of ASR products in thin cracks.

The expansion of the concretes is being continuously monitored. Long term monitoring may be necessary to see the full extent of expansion and mitigation, particularly for the 38 °C concrete prisms, since alkali boosting was intended to simulate cements of higher alkali contents and not to accelerate the expansion like in conventional CPT.

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6. REFERENCES

[1] Shayan, A., The current status of AAR in Australia and mitigation measures. Concrete in Australia, 2015. 41(2): pp 44-51.

[2] Shayan, A. Use of Fly Ash and Blended Slag Cement in Prevention of Alkali-Aggregate Reaction in Concrete. in "Concrete for the Nineties", Proceedings of the International Conference on the Use of Fly Ash, Slag, Silica Fume and other Siliceous Materials in Concrete. 1990. Leura, New South Wales.

[3] Shayan, A., R. Diggins, and I. Ivanusec, Effectiveness of Fly Ash in Preventing Deleterious Expansion due to Alkali-Aggregate Reaction in Normal and Steam-Cured Concrete. Cement and Cocrete Research, 1996. 26: pp 153-164.

[4] Thomas, M., The effect of supplementary cementing materials on alkali-silica reaction: A review. Cement and Concrete Research 2011. 41: pp 1224-1231.

[5] Duchesne, J. and M.-A. Berube, Long-term effectiveness of supplementary cementing materials against alkali–silica reaction. Cement and Concrete Research 2001. 31: pp 1057-1063.

[6] Thomas, M.D.A., et al., Effect of fly ash on the expansion of concrete due to alkali-silica reaction – Exposure site studies. Cement & Concrete Composites, 2011. 33: p. 359-367.

[7] Hooton, D., et al., Twenty-Year Field Evaluation of Alkali-Silica Reaction Mitigation. ACI MATERIALS JOURNAL, 2013: pp 539-548.

[8] Thomas, M., et al., Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete. Cement and Concrete Research 2006. 36: p. 1842-1856.

[9] Sirivivatnanon, V., et al., Reliability of extending AS1141.60.1 and 60.2 test methods to determine ASR mitigation, in Concrete 2019 "Concrete in Practice-Progress Through Knowledge". 2019: Sydney, Australia.

[10] Sirivivatnanon, V., J. Mohammadi, and W. South, Reliability of new Australian test methods in predicting alkali silica reaction of field concrete. Construction and Building Materials, 2016. 126 pp 868-874.

[11] Islam, M.S., et al., Role of Solution Concentration, cement alkali and test duration on expansion of accelerated mortar bar test. Materials and Structures, 2016. 49: pp 1955-1965.

[12] Rivard, P., et al., Decrease of pore solution alkalinity in concrete tested for alkali-silica reaction. Materials and Structures 2007. 40: p. 909-921.

[13] Einarsdottir, S.U. and R.D. Hooton, Modifications to ASTM C1293 that Allow Testing of Low Alkali Binder Systems. ACI Materials Journal, 2018. 115(5).

[14] Thomas, M.D.A., et al., Performance Limits for Evaluating Supplementary Cementing Materials Using Accelerated Mortar Bar Test. ACI MATERIALS JOURNAL, 2007: pp 115-122.

[15] Lindgård, J., et al., Alkali–silica reactions (ASR): Literature review on parameters influencing laboratory performance testing. Cement and Concrete Research 2012. 42: pp 223-243.

[16] Chappex, T., et al. A Robust Testing Protocol for the Assessment of ASR Reactivity of Concrete. in 15th International Conference on Alkali Aggregate Reaction in Concrete (ICAAR). 2016. São Paulo Brazil.

[17] Andreas Leemann, T.K., Isabel Fernandes, Maarten A. T. M. Broekmans, Raman microscopy of alkali-silica reaction (ASR) products formed in concrete. Cement and Concrete Research, 2017. 102: pp 41-47.

[18] Fernandes, I., Composition of alkali–silica reaction products at different locations within concrete structures. Materials Characterization, 2009. 60: pp 655-668.