Mitigation of ASR using aggregate fines as an alternative for SCMs

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Abstract

The use of supplementary cementitious materials (SCMs) for mitigating alkali-silica reaction (ASR) is the most common and practical approach adopted by concrete producers since the early 1950s [1]. However, with the future supply of commonly available SCMs such as fly ash and ground granulated blast furnace slag set to decline, alternative materials for mitigating ASR needs to be considered. The objective of this experimental work is to investigate the potential of using ground reactive aggregate fines as SCM substitutes to mitigate ASR. The mechanism of mitigation has been investigated using characterization and expansion tests assessed under AMBT conditions. Mortar bars containing 0%, 10%, 25% and 40% ground reactive aggregate fines by mass of cement replacement were prepared for modified accelerated mortar bar testing. The results obtained indicated that a reduction in ASR expansion was achieved with increasing ground reactive aggregate fines content. Further characterization including XRF and ICP-OES analyses were carried out on ground reactive aggregate fines to understand the efficacy of these materials as potential additives for ASR mitigation.

Keywords*: alkali-silica reaction (ASR); ground reactive aggregate fines; mitigation; supplementary cementitious materials (SCMs)*

1. INTRODUCTION

1.1 Mechanism and mitigation of ASR

Alkali-silica reaction (ASR) in concrete arises from the reaction of alkali in concrete pore solution and reactive silica found in aggregates. The chemical mechanism of ASR reaction is well documented in literature [2-4]. Deleterious ASR occurs in the presence of high alkali in the pore solution, reactive silica and sufficient moisture. ASR can lead to the formation of a hygroscopic gel, which is expansive upon absorption of moisture. Any confinement of stress induced by the expansive gel can lead to subsequent cracking causing damage to the concrete structure.

Since the discovery of ASR [5], several studies have been conducted on strategies to mitigate this reaction. Literature findings have established that using SCMs such as fly ash and granulated blast furnace slag added in the right proportions have high mitigative properties against ASR [2, 6, 7]. The main mechanism by which SCMs hinders deleterious alkali-silica reaction is by reducing the amount of alkalis that are available in the pore solution through a pozzolanic reaction that occurs over time [2, 8]. Some of the factors that affect the effectiveness of an SCM are particle fineness and silica content. Typically, SCMs with high fineness and SiO_2 contents have high efficacy to mitigate ASR [7, 9]. Due to their increased surface area, large amounts of reactive silica is released to rapidly react with the available alkali in the pore solution. This reduces the amount of alkali in the pore solution that will react with potentially reactive aggregate particles to form deleterious ASR.

Other SCM mitigation mechanisms include micro-filling and densification of pore structures in the concrete, thus, restricting the ingress of moisture throughout the concrete. This is achieved by the fine

particle size of SCMs [10]. Additionally, the partial replacement of cement by SCMs inadvertently results in less cement used in the concrete mix. This decreases the total amount of alkali that is made available to react with coarse aggregate in the formation of ASR. This phenomenon is reported as the dilution effect [11]. While the concept of dilution is largely accepted, it has also been reported that some SCMs may contain alkalis that can be released slowly over time thus ultimately providing potentially reactive aggregates with alkali to form ASR [12].

1.2   Potential materials for ASR mitigation

Reactive aggregates, like SCMs, also have high free silica content that can be released in a high alkali environment and thus when ground may yet present as an alternative for conventional SCMs for ASR mitigation in concrete. Reactive aggregates are typically classified as aggregates that contain certain disordered quartz phases such as amorphous and strained quartz as well as reactive minerals including opal and volcanic glass of rhyolitic composition. The reactive nature of an aggregate can be obtained through characterization techniques such as petrography, as well as chemical and standardized expansion tests including the accelerated mortar bar test (AMBT) and the concrete prism test (CPT).

The recommended practice for concrete mix design uses a specific size grading aimed at improving the compatibility, density, workability and strength of the concrete. Therefore, very fine aggregate particles (typically less than 125 µm in size) are generally discarded. However, some studies report that the use of very fine reactive aggregate particle sizes could aid in the reduction of ASR expansion by assuming a pozzolanic role [13]. This can be possible with aggregates that show high potential to alkali reactivity. In this way, the mechanism of mitigation is expected to be similar to that of conventional SCMs such that appropriate fractions of very fine particles of a siliceous reactive aggregate can be added to concrete to create a pozzolanic reaction, and encourage micro-filling of pores limiting the progression of moisture for ASR [14]. The objective of the study, therefore, is to investigate the potential use of ground reactive siliceous aggregate fines as SCM substitute for mitigating ASR.

At present, the supply of commonly available SCMs such as fly ash and granulated blast furnace slag is set to decline and may become unavailable in the future. These conventional SCMs are obtained as by-products of other engineering operations. More so, in certain regions, SCMs are not readily available as an option for use in concrete due to their high cost. Therefore, obtaining alternative mitigating materials or investigating mitigation strategies is essential for the future of concrete. The use of ground reactive aggregate fines has economic benefits as these materials are likely to be readily and abundantly available at quarries that supply (particularly) manufactured sand thus saving cost. Furthermore, the fine particles that result from crushing of larger rocks are usually discarded as waste material; incorporating these materials into the concrete conserves natural resources in this regard and thus preserves the environment.

2.   MATERIALS AND METHODS

2.1   Materials

2.1.1   Reactive aggregate

A sand blend consisting of 40% Australian non-reactive sand and 60% New Zealand reactive sand was selected as the main aggregate combination for this study. This sand blend was found to be reactive under AS1141.60.1 accelerated mortar bar test conditions [15]. Although the New Zealand reactive sand is known to be reactive from field experience and previous research studies [16, 17], a recent study suggests that a sand blend consisting of the New Zealand reactive sand and Australian non-reactive sand could potentially be used for concrete supply; however, further mitigation strategies against ASR may be required [15]. In a commercial study conducted using the concrete prism test (CPT) in accordance with AS1141.60.2 and using a non-reactive coarse aggregate, an expansion below the Australian CPT limit of 0.04% was observed for this sand blend after 12 months of testing. At the end of 24 months, a CPT expansion of 0.07% was reached.

2.1.2   Ground reactive aggregate fines as potential additives for ASR mitigation

To determine the potential of ground reactive aggregate fines as an additive for mitigating ASR, a rhyolitic manufactured sand (RA) and a reactive natural sand (NA) have been selected as ground reactive aggregate fines for replacement by mass of cement in mortar bars. The aggregates (RA and NA) were ground in a vibratory disc mill. The average particle size of the ground reactive aggregate

fines was analysed using a Malvern Mastersizer 3000 and found to be 107 μm. The oxide composition of the selected aggregates, determined through XRF analyses, is given in Table 2.1. Furthermore, the reactivity of NA and RA was also investigated using accelerated mortar bar expansion tests to determine their efficacy as potential additives for ASR mitigation.

2.1.3 Cement

A low alkali OPC cement was chosen as the binder for mortar bars in this study. The alkali content of the cement was determined by XRF as 0.58% Na_2O_e (Table 2.2). This cement was selected because the alkali content conforms to the current alkali limit set for cement in Australia and New Zealand [18, 19] and thus is representative of the cement that is used in field structures.

Table 2.1: Oxide composition of ground reactive aggregate.

Element Oxide wt.%	Rhyolitic Manufactured Sand (RA)	Reactive Natural Sand (NA)
Na_2O	5.65	4.31
MgO	1.57	1.43
Al_2O_3	15.44	14.21
SiO_2	61.93	63.93
P_2O_5	0.18	0.04
SO_3	0.07	<0.01
K_2O	2.89	1.09
CaO	2.30	3.46
TiO_2	0.81	0.55
Mn_3O_4	0.10	0.09
Fe_2O_3	5.75	4.45
LOI	4.09	7.08
TOTAL	100.83	100.66

Table 2.2: Chemical composition of Portland cement.

Component	%
CaO	64.55
SiO_2	20.79
Al_2O_3	3.80
Fe_2O_3	2.52
MgO	0.95
Mn_2O_3	0.08
K_2O	0.50
Na_2O	0.25
P_2O_5	0.18
SO_3	2.25
TiO_2	0.28
LOI	3.20
Total	99.35
Total Alkali as Na_2O Eq.	0.58

Table 2.3: Mix proportions for mortar bars investigated in this study.

Sample Group	Cement Content (%)	Ground reactive Aggregate fines (%)	Amount of sand blend (g)
OPC	100	0	990
10% (RA", NA")	90	10	990
25% (RA", NA")	75	25	990
40% (RA", NA")	60	40	990

RA" = Ground rhyolitic manufactured sand; NA" = Ground reactive natural sand

2.2 Test methods

2.2.1 Accelerated mortar bar test

The mortar bars investigated were prepared and tested following Australian standard AS1141.60.1 [20]. This method follows a similar procedure to ASTM 1260, however, the expansion limits and reactivity classification differ as described in Table 2.4. Mortar bars are prepared with a w/c ratio of 0.47 and stored in 1M NaOH at 80°C for up to 21 days. For this study, the expansion of mortar bars was monitored for an extended test period of 56 days. Three mortar bars of dimensions 25 mm x 25 mm x 285 mm were prepared for each sample group described in Table 2.3.

Table 2.4: AMBT aggregate reactivity classification by AS1141.60.1.

Mean mortar bar expansion (E) %		Aggregate Reactivity classification
Duration of specimens in 1 mol/L NaOH at 80oC		
10 days	21 days	
-	E < 0.10*	Non-reactive
E < 0.10*	0.10* ≤ E< 0.30	Slowly reactive
E ≥ 0.10*	-	Reactive
-	0.30 ≤ E	Reactive

* The value for natural fine aggregates is 0.15%

2.2.2 Characterization of dissolved silica from the ground reactive aggregate fines

The ground reactive aggregate fines were also immersed in 1M NaOH at 80°C and the concentration of released silica (free Si) was determined by ICP-OES after 24 hours of testing.

3. RESULTS AND DISCUSSION

3.1 Accelerated mortar bar tests (AMBT)

Figures 3.1 show the AMBT expansion for the rhyolitic manufactured sand (RA) and reactive natural sand (NA) used as ground reactive aggregate fines for ASR mitigation in mortar bars. From the results obtained, both aggregates RA and NA exceeded the expansion limits of 0.1% (0.15% for natural reactive sand) at 10 days and 0.3% at 21 days as stipulated in AS1141.60.1 (Table 2.4). Therefore, both RA and

NA can be classified as reactive. However, the NA was seen to show higher expansion thus reactivity than the RA.
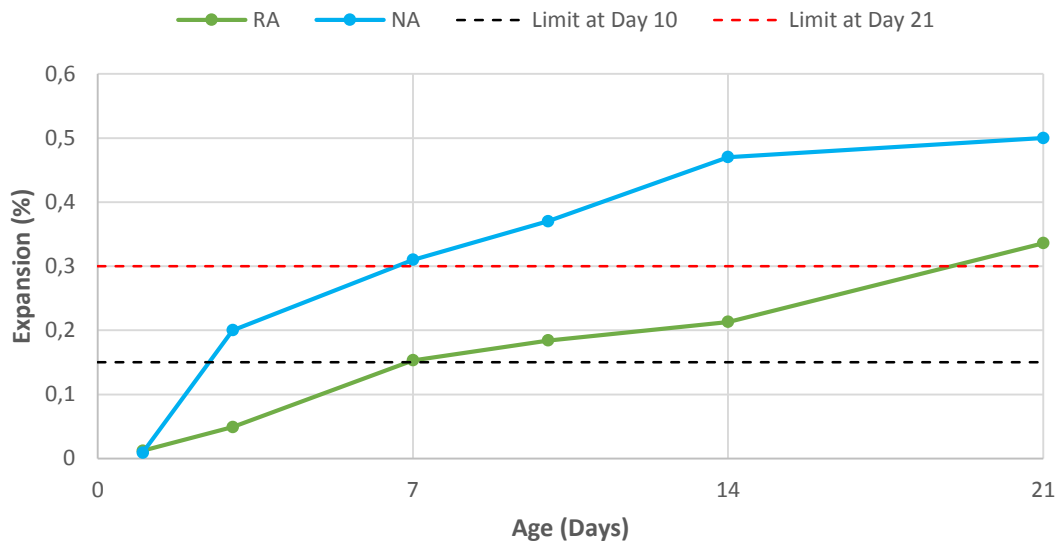

Figure 3.1: AMBT expansion results for aggregates intended for use as ASR mitigating additives (RA= rhyolitic manufactured sand; NA= reactive natural sand).

The AMBT expansion results of mortar bars prepared with ground reactive aggregate fines at varying cement replacement levels are shown in Figures 3.2 and 3.3. Owed to the natural sand blend used in this study, as per the AS1141.60.1 test method, the expansion limits of 0.15% at 10 days and 0.3% at 21 days (Table 2.4) were used to determine the effect of the ground reactive aggregate fines on ASR mitigation. The 21-day expansion limit of 0.3% was also selected as the expansion limit for the extended test duration of 56 days.
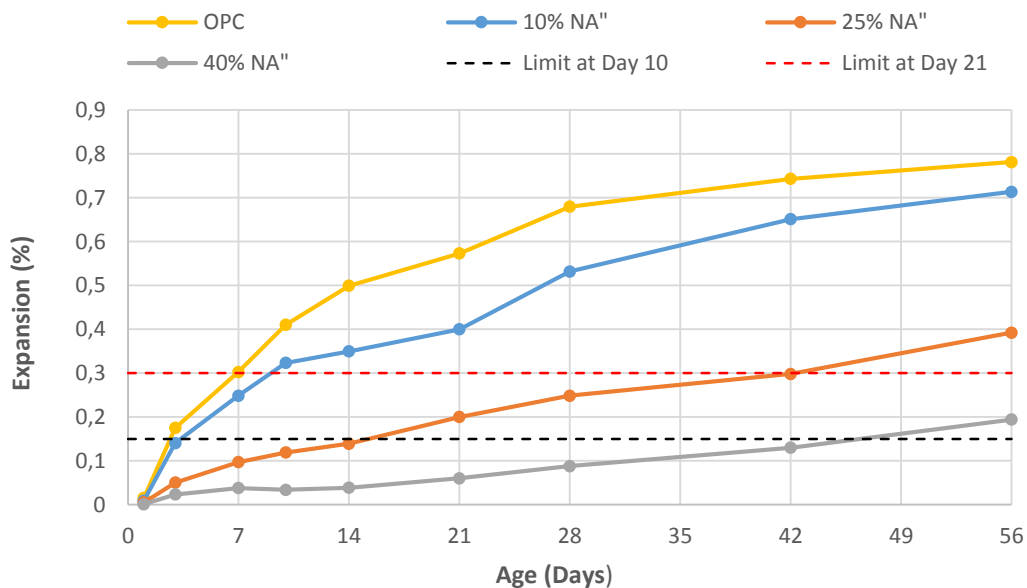

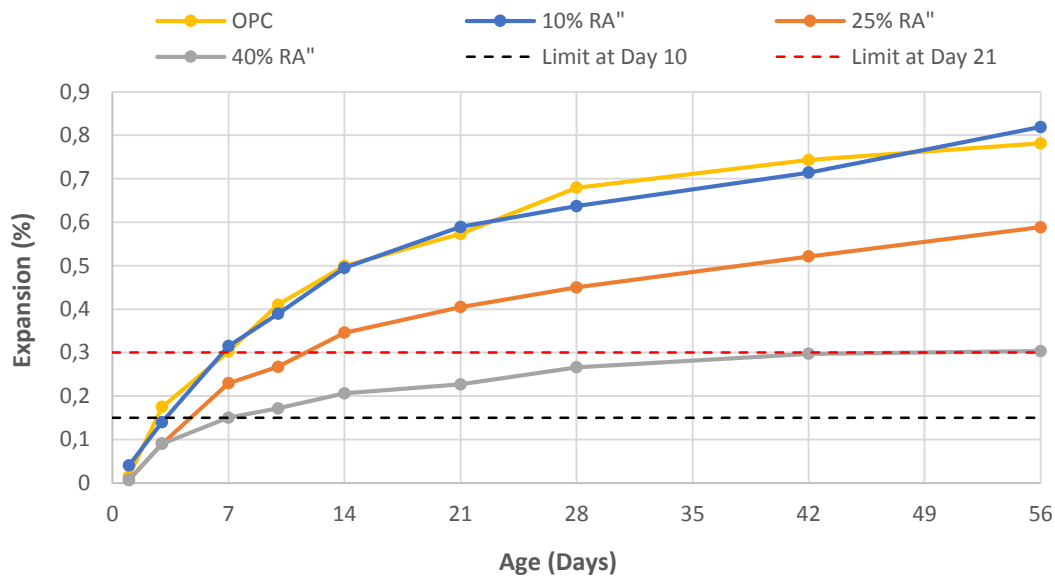Figure 3.2: AMBT expansion of mortar bars containing ground reactive natural sand (NA") for ASR mitigation.

Figure 3.3: AMBT expansion of mortar bars containing ground rhyolitic manufactured sand (RA") for ASR mitigation.

Generally, a decrease in expansion was observed with an increasing amount of ground reactive aggregate fines. For mortar bars containing ground reactive natural sand (Figure 3.2), specimens with 0% and 10% replacement of cement (OPC and 10% NA") can be classified as reactive at the end of 21 days in accordance to the limits stipulated in AS1141.60.1. However, when the amount of ground reactive natural sand is increased to 25% and 40% at 21 days, the expansion was seen to decrease significantly to 0.2% and 0.06% thus classifying these mortar mixes as non-reactive. At the end of the 56 days, all mortar bars exceeded the 0.3% expansion limit except for bars containing 40% ground reactive natural sand which recorded an expansion of 0.19%.

Conversely, a higher expansion was observed for specimens containing ground rhyolitic manufactured sand, although ASR mitigation was still evident. Mortar bars containing 10% ground rhyolitic manufactured sand (Figure 3.3) showed expansion similar to mortar bars with 0% additive (OPC). At 25% replacement of cement (25% RA"), a decrease in expansion was observed, however, the expansion limits of 0.15% and 0.3% at 10 and 21 days respectively were exceeded. The mix can, therefore, be classified as reactive to ASR. For mortar bars containing 40% RA", a slowly reactive behaviour was observed with an expansion of 0.17% at 10 days and 0.23% at 21 days. Similar to specimens containing ground reactive natural sand at 56 days, all specimens showed expansion exceeding 0.3%.

Related studies conducted using different aggregates and testing methods arrived at a similar conclusion: that reactive aggregates may present ASR mitigative properties comparable to conventional SCMs [21, 22].

3.2   Characterization of ground reactive aggregate fines

The efficacy of the ground reactive aggregate fines for use as partial replacement of cement in mitigating ASR can be further understood by the applying additional characterization methods to better understand the behaviour of these materials. From the AMBT expansion results of mortar bars containing ground reactive aggregate fines (Figures 3.2 and 3.3), it can be seen that the ground reactive natural sand showed higher efficacy in mitigating ASR than the ground rhyolitic manufactured sand. This observation can be justified by the determination of silica released by both aggregates in 1M NaOH at 80°C. The amount of dissolved silica in solution as determined using ICP-OES is represented in Table 3.1. From this data, it can be seen that ground reactive natural sand releases 5 times more silica than ground rhyolitic manufactured sand. This confirms the trend in reactivity also seen in the AMBT expansion results for the aggregates (Figure 3.1). Therefore, the greater the reactivity potential of an aggregate, the greater the amount of silica will be released from finer particles resulting in a greater potential for ASR mitigation.

Table 3.1: Silica release from ground reactive aggregate fines intended for use as an additive for ASR mitigation.

Ground Reactive Aggregate Fines	Dissolved Silica @ 80oC for 24 hrs (mmol/L)
RA"	27.46
NA"	124.9

Further to the XRF conducted on ground reactive natural sand and ground rhyolitic manufactured sand (Table 2.1), which shows that ground reactive natural sand had a slightly higher amount of silica than ground rhyolitic manufactured sand, petrographic assessments of aggregates RA and NA are currently ongoing to understand the mineralogical composition of the aggregates with respect to their observed silica release and reactivity.

4. CONCLUSION

The use of ground reactive aggregate fines has been studied as a potential additive for reducing ASR in mortars and concretes. In this study, 2 types of aggregates; reactive natural aggregates and rhyolitic manufactured aggregate, have been investigated. From the results obtained, the following conclusions can be made;

1. The potential exists for the use of ground reactive aggregate fines as additives for mitigating ASR in mortars and concretes.
2. For this study, finely ground reactive aggregates of approximately 107 µm in size showed an effective reduction of expansion due to ASR. A further decrease in the particle size of the reactive aggregates to cement fineness could potentially increase the effectiveness of the ground reactive aggregates in reducing ASR.
3. Ground reactive aggregate fines that release high Si (free silica) in solution has a high potential for use as an additive for mitigating ASR. Accordingly, these aggregate tend to cause deleterious ASR when used in their natural as-received (fine or coarse) form.

5. ACKNOWLEDGEMENT

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