

REACTIVITY OF RECLAIMED CONCRETE AGGREGATE PRODUCED FROM CONCRETE AFFECTED BY ALKALI SILICA REACTION

Medhat Shehata^{1*}, Chris Christidis², Waleed Mikhael¹,
Chris Rogers³ and Mohamed Lachemi¹

¹Department of Civil Engineering, Ryerson University, TORONTO, ON, Canada

²Lafarge North America, MISSISSAUGA, ON, Canada

³Ontario Ministry of Transportation, TORONTO, ON, Canada

Abstract

This paper presents results from a research program that focused on studying the reactivity of reclaimed concrete aggregate (RCA) produced from concrete affected by alkali silica reaction (ASR). The results showed that RCA produced from ASR-affected concrete causes significant expansion when used in new concrete. The expansion was similar to that produced in concrete containing the reactive aggregate used originally in the old concrete. It is believed that crushing the old concrete exposed fresh faces of the reactive aggregate which causes expansion in the new concrete. The alkalis contributed from the RCA are also believed to contribute to the expansion. The amount of supplementary cementing materials required to mitigate the expansion in new concrete containing ASR-affected RCA was higher than those needed in concrete containing the virgin reactive aggregate. The results showed a good agreement between the 14-day expansion of accelerated mortar bars and the 2-year expansion of concrete prisms.

Keywords: Aggregate reactivity, supplementary cementing materials, reclaimed concrete aggregate, lithium salts, alkali level

1 INTRODUCTION

Environmental issues resulting from construction waste are a major concern. Each year 200 million tons of construction waste is continuously discarded in landfills [1]. Most of the disposed construction materials can be recycled, thus reducing the accumulation of waste disposed in landfills. Concrete is of great concern when considering wasted materials as it constitutes the largest portion of the total debris after demolition. For example, when an apartment is demolished concrete amounts to approximately 30 to 40% of the wreckage [2].

With time structures deteriorate to a point where repair is not cost effective, and as a result the structure will need to be replaced. The debris that remains after demolition is often removed and taken to landfill sites. As landfills become crowded and more heavily regulated, it makes sense to seek possible uses of these materials such as recycling into new structures. In Ontario, specifications currently permit the recycling of RCA as granular base in pavements. Recycling demolished concrete as aggregate in new concrete is also an option that not only reduces the amount of construction wastes disposed in landfills but also reduces the consumption of non-renewable resources, such as natural aggregate. However, the use of reclaimed concrete aggregate (RCA) in new structures requires thorough research to make sure that the durability of the new concrete is not compromised, especially if the old concrete was suffering from alkali-silica reaction.

Many* highway and hydraulic structures in North America have been reported to be affected by alkali silica reaction (ASR). In Ontario alone, and as early as the beginning of the 1980's, it was reported that more than 130 highway structures were affected by alkali-aggregate reaction [3]. It is anticipated that some of these structures will be demolished as they approach the end of their service life. Recycling of the reclaimed concrete in new structures may be a viable option from environmental and economic standpoints, especially if the structures are in locations that are far from natural aggregate sources. So, it is imperative to investigate the potential reactivity of the reclaimed aggregate and develop preventive measures, if needed.

The use of supplementary cementing materials (SCM) as preventive measures against ASR has been adopted in many new structures. Much research has shown that the use of the right amount and type of SCM reduces the expansion due to ASR to a very low level [4-7]. The efficacy of these

* Correspondence to: mshahata@ryerson.ca

materials in mitigating ASR is attributed, mainly, to their ability to reduce the alkalinity of pore solution [8]. Field observations of structures containing SCM have also shown good performance [9].

Lithium salts have been reported by various researchers to be effective, when used in appropriate dosages, in counteracting ASR [10-14]. Lithium nitrate has been found to be the most effective salt as it does not raise the alkalinity of the pore solution as is the case with lithium hydroxide [11]. The appropriate dosage of lithium has been found to have no correlation with the aggregate expansivity or the petrographic nature of the aggregate [12]. Research has also shown that considerable amounts of lithium are bound by the hydration products of the cementing materials [13]. The mechanism by which lithium mitigates ASR is not fully known. One of the mechanisms put forward by Kurtis et al. [14] suggests that lithium reduces the repolymerization of ASR gel, and hence reduces its ability to expand. However, the study of Kurtis et al. was performed using lithium chloride.

There has been very limited research conducted on the reactivity of RCA produced from ASR-affected concrete. A study, in the United States, on RCA from a section of Interstate I-95 near Gardener, Maine, showed that ASR affected RCA causes high expansion in the new concrete. The expansion was higher than that produced in concrete containing the aggregates originally used in the concrete which was a fine-grained quartzite coarse aggregate [15].

The main objectives of the research presented in this paper were: (1) to investigate the reactivity of RCA produced from ASR-affected concrete containing highly reactive Canadian aggregate, (2) to find out if current ASR tests including the accelerated mortar bar test are able to evaluate the reactivity of RCA and the efficacy of common preventive measures such as SCM, and (3) to determine the type and levels of preventive measures that are needed to mitigate the expansion in new concrete containing ASR-affected RCA.

2 MATERIALS AND METHODS

2.1 Origin of reactive RCA

The RCA used in this study was obtained from the Ontario Ministry of Transportation outdoor exposure site in Kingston, Ontario, Canada [16]. The concrete was part of a concrete block placed in 1991 with General Use (Type 10) Portland cement (GUPC) and highly reactive siliceous limestone coarse aggregate from Ottawa, Ontario (Spratt). After 12 years of exposure, the block was removed and crushed into aggregate. At that time, the concrete block had experienced severe expansion and cracking. The concrete block was broken into boulder-size pieces using a backhoe ram and a jaw crusher used to produce coarse and fine RCA.

2.2 Materials and mix designs

The Dry Bulk Relative Density and absorption of the coarse RCA were 2333 kg/m³ and 5.07%, respectively. Samples of Spratt aggregate (the virgin aggregates originally used in the RCA) were also collected from a stockpile at the Ontario Ministry of Transportation. Two GU Portland cements (PC) of low and high alkali contents and six different SCM's were used in the study. The chemical analysis of the PCs and SCM are listed in Table 1. The use of Lithium nitrate (LiNO₃) was also investigated as a preventive measure.

The mixture proportions for concrete and mortar samples used in the concrete prism and accelerated mortar bar tests were according to the applicable test methods and are noted below in Subsection 2.3.

2.3 Methods for assessment and analysis

Concrete Prism Test

The concrete prism test (CPT) [CSA A23.2-14A] was used to evaluate the reactivity of the RCA and the efficacy of preventive measures. Using the 60:40 coarse-to-fine aggregate ratio by mass resulted in a coarse mix, which was expected since the RCA has a relatively low relative density. A volume of dry-rodded coarse aggregate of 0.69% of unit volume of concrete was found to produce workable and homogeneous mixtures. This ratio, which lies within the limit of CSA A23.2-14A, was then used in all the tested samples. The RCA was not washed so as to eliminate any leaching of alkalis from the residual mortar. However, a control concrete mixture (with no SCM) was prepared with washed RCA aggregates to investigate the effects of washing on reactivity.

To examine the effects of alkali loading on expansion, additional control samples (with no SCM or lithium nitrate) were prepared at alkali levels of 0.55%, 0.80% and 1.5% Na₂O_e. The 0.80 Na₂O_e was achieved by mixing the two GU cements of 0.96% and 0.56% Na₂O_e at the required ratio.

The SCMs listed in Table 1 were used at different replacement levels in binary and ternary blends with the high-alkali GU Portland cement following the standard. Lithium nitrate was also investigated at different dosages. Some samples were tested by adding the lithium to the mixing water

while others were tested by pre-soaking the air dry RCA in the lithium and half of the mixing water for 24 hours prior to mixing.

Accelerated Mortar Bar Test

The accelerated mortar bar test (AMBT) was conducted following ASTM C1260 and ASTM C1567 with the objective of investigating whether or not this test method was able to evaluate the reactivity of RCA and the efficacy of SCMs as preventive measures. The results from the concrete prism test were used as a benchmark to evaluate the suitability of the AMBT in testing RCA. Mortar samples without SCM were tested following ASTM C1260 and those with SCM following ASTM C1567. The aggregate samples were prepared by crushing and sieving the coarse RCA to the required gradation as per test method. The fine fraction produced by the primary crushing (first crushing by jaw crusher) was found to produce considerably lower expansion than the sample prepared by crushing the coarse RCA (secondary crushing), as will be shown in Figure 7. Based on that, all accelerated mortar bar tests were performed using aggregate produced by crushing and sieving the coarse RCA.

Scanning Electron Microscopy (SEM)

Polished thin sections were prepared and sputtered with carbon in an Edwards Vacuum Coating System Model # 306A using ultra pure Carbon, Grade UF4S. The sections were analysed in a JEOL JSM6380LV scanning electron microscope equipped with Oxford INCA x-sight Energy Dispersive X-Ray analysis (EDS) System. The backscattered electron images (BSE) were taken at an accelerated voltage of 20Kv under high vacuum of about 1^{-4} Torr and probe current in the range from 1pA to 1 μ A.

3 RESULTS

Figure 1 shows the expansion of control concrete prisms (with no SCM) containing either coarse or fine RCA as well as prisms containing the virgin aggregate originally used in the RCA (Spratt). Two identical control concrete prism samples were tested to investigate the range of concrete expansions values that can be produced using RCA from the same source. Two expansion curves for Spratt are also presented in Figure 1: a curve from Shehata and Thomas' study, 2000 [6] and another one from a sample tested in this RCA research program. It is clear from the expansion curves that the RCA produces expansion similar to that of the Spratt. In addition, 18 hours of washing the RCA with running water did not result in a significant reduction in the expansion. Figure 1 also shows that the RCA fine aggregate when test with a non-reactive coarse aggregate exceeded the 0.04% expansion limit at 1 year.

The effect of alkali loading or cement alkali content on the expansion of concrete prisms containing coarse RCA and virgin Spratt is shown in Figure 2. While PC of 0.70% Na_2O_e resulted in a 1-year expansion $< 0.04\%$ for concrete prisms with Spratt, a PC of alkali content = 0.56% Na_2O_e did not reduce the expansion of concrete with RCA below the 0.04% limit. This is probably due to the alkalis contributed from the RCA.

The effects of different binary and ternary blends of SCM on the expansion of concrete with RCA and concrete with virgin Spratt are shown in Figures 3 through 6. The expansion results for concrete with Spratt are obtained from an earlier study [17] using SCM's of similar chemical composition to those used with the RCA but not necessarily from the same sources. Figure 3 compares the 2-year expansions of concrete containing Spratt with those of concrete containing RCA. It is clear from the graph that RCA requires higher levels of low and high-calcium fly ashes to mitigate the expansion, compared to the levels required for Spratt. Indeed, 50% CH-LA fly ash was enough to give a 2-year expansion below the 0.04% expansion limit in the case of concrete with Spratt, but more than 70% would be required to give the same level of expansion in concrete with RCA, as can be determined by extrapolating the curve in Figure 3. The same can be said for all other SCMs including binary and ternary blends as shown in Figures 4 and 5. Figure 4 shows that up to 12% SF was not enough to suppress the expansion in concrete with RCA but 10% was enough for concrete with Spratt. The results of ternary blends containing 5% SF and different levels of SCM are shown in Figure 5 which also confirmed that RCA requires higher levels of SCM than Spratt to mitigate the expansion. The sample containing 5/25 SF/CI LA had an expansion of 0.041% at 2 years, which can be considered as marginally meeting the 2-year expansion criterion of 0.04%.

The results shown in Figure 6 for F-HA fly ash are obtained using the same fly ash for both Spratt and RCA. This fly ash was not effective, when used as the sole SCM, in mitigating the expansion for Spratt which is attributable to its high alkali content (4.30% Na_2O_e). When used at replacement levels of 20% or 25% with 5% silica fume, the blends were effective with Spratt but not

with RCA. This supports the results in Figure 3 to 5 that higher levels of SCM are required to mitigate expansion in concrete with ASR-affected RCA.

Figure 7 compares the accelerated mortar bar expansions of fine RCA produced initially by crushing the deteriorated concrete (primary crushing) and the expansion of crushed and sieved coarse RCA (secondary crushing). The higher expansion of the secondary crushed RCA is probably attributable to its higher reactive aggregate content. Fine aggregate produced initially from the deteriorated concrete is expected to be composed mainly of weaker mortar rather than coarse aggregate. All the other AMBT conducted in this study contained only crushed coarse RCA (secondary crushing). Figure 8 demonstrates that there is a good correlation between the 14-day expansion from the AMBT and the 2-year expansion from the CPT (or 1 year in case of the standard control sample with no SCM). However, more testing is needed to see if the trend still exists for samples with CPT expansion lower than 0.04% at two years.

Figure 9 shows the expansion at 1 year of concrete prisms containing different levels of lithium nitrate expressed as $\text{Li}/(\text{Na}+\text{K})$ molar ratio of the alkalis in the mix, without considering the alkalis contributed from the RCA. Presoaking the aggregate in lithium solution and half the mixing water did not have much positive effect on mitigating the expansion. As Figure 9 shows, all the tested dosages resulted in concrete expansion higher than the 0.04% expansion limit at the age of 1 year. However, there was a considerable reduction in the expansion compared to sample with no lithium or samples with binary blend of SCM.

4 DISCUSSION

The results presented in Figure 1 confirm that the ASR affected RCA used in this study would produce significant levels of disruption if used in new concrete without appropriate preventive measures. The level of expansion would be similar, if not higher, than that produced in concrete containing the original virgin aggregate used in the RCA. The high expansion of concrete containing the RCA can be attributable to one or a combination of the following reasons: (1) the significant amount of alkalis contributed from the residual mortar in the RCA, (2) expansion of the existing ASR gel in the RCA when exposed to high level of moisture in the new concrete, and (3) exposing new or fresh faces of the reactive virgin aggregate during crushing and processing of RCA. Examining RCA particles under the scanning electron microscope (Figure 10) showed the presence of ASR gel within the Spratt reactive aggregate in RCA particles. The right image in Figure 10 also shows empty cracks within the Spratt aggregate in the RCA. These types of cracks are produced, most likely, during crushing and processing of the old concrete to produce the RCA. It is possible that the presence of these cracks promotes more reaction and expansion in the new concrete by providing an easy access for alkalis to reaction sites within the aggregates.

It was assumed that washing the RCA would wash out large amount of alkalis from the residual mortar in the RCA and hence result in lower expansion. The obtained high expansion value suggests that the 18 hours of washing were not enough to wash out considerable amount of alkalis, and/or there are enough alkalis from the new PC used in the new concrete to trigger expansion in the freshly exposed reactive Spratt in the RCA.

Figure 1 also shows that fine RCA produces less expansion compared to coarse RCA. This is attributable, most likely, to the lower reactive aggregate and higher residual mortar contents in the fine RCA. Other research work [20] has shown that using fine powder of reactive aggregate along with the same aggregate can reduce the expansion through the pozzolanic activity of the powder. This finding is unlikely to be a major cause of the lower expansion of the fine RCA investigated here. This is because the amount of powder or materials finer than $80\ \mu\text{m}$ in the RCA was very limited compared to the amount of powder investigated in ref [20]. In addition, the powder produced from siliceous limestone aggregate (of similar main composition as that of the Spratt contained in the RCA) was found to have the least reduction in expansion compared to the other tested aggregates, e.g. glass, quartzite and opal [20].

The authors believe that the alkalis contributed from RCA was the reason behind the higher expansion of concrete with RCA compared to that of concrete with Spratt when PC of alkali contents $< 0.80\%$ are used (Figure 2). This trend did not continue at PC of higher alkali contents. Indeed, the expansion of RCA-concrete was similar to that of the Spratt-concrete at PC of alkali content = 1.25% . This can be explained based on the behavior the reactive aggregate under investigation (Spratt) which shows very little further expansion beyond an alkali content of $4.20\ \text{kg}/\text{m}^3$ of concrete or 1.00% Na_2O_e of the PC, as shown in Figure 2 and reported elsewhere [6]. This is also the reason behind the similar expansion values obtained for RCA-concrete with PC of alkali contents of 1.25% and 1.50% Na_2O_e as shown in Figure 2.

Since the main mechanism by which SCM's reduce expansion due to ASR is by binding alkalis from concrete pore solution [6,7], one would expect that systems of higher alkali contents would require higher levels of SCM to lower the pore solution alkalinity to a "safe level". This indeed was the case in this study where the RCA required higher levels of SCM than virgin Spratt aggregate to achieve the same level of expansion, as shown in Figures 3 to 6. The alkalis contributed from the residual RCA paste contributed to the total alkalis in the concrete mixtures. Scott and Gress [15] also found that higher levels of SCM were required to mitigate expansion in concrete containing RCA with fine-grained quartzite aggregate.

An interesting observation, though, is that the Intermediate Calcium (CI-LA) fly ash used in this study achieved better results than the Low-Calcium (F-LA) ash. This could be attributable, at least partly, to the higher fineness of the CI ash used in this study compared to the F ash (14.9% versus 26.7% retained on 45 μm -sieve for CI and F ashes, respectively as listed in Table 1). In addition, earlier research work [6] has shown that Low and Intermediate calcium fly ashes (up to CaO content of 20%) perform more or less equally in terms of resisting ASR, as long as their alkali contents are similar.

The results showed that the AMBT can be used to evaluate the reactivity of RCA and the efficacy of SCM as preventive measures. The same finding has been reported in other research work for natural reactive aggregate tested with different blends of SCM [6, 18]. Although more testing is needed to see whether or not samples that pass the CPT also pass the AMBT, the fact that none of the samples tested in this study passed the 0.10% expansion criterion of the AMBT and failed that of the CPT (0.04%) provides some comfort that the AMBT does not underestimate the expansion of concrete prisms (Figure 8). It is very important, however, to make sure that the RCA tested in the AMBT is produced by crushing and grading the coarse RCA (secondary crushing) since fine RCA produced by initial crushing of the old concrete (primary crushing) was found to be less reactive (Figure 7). In addition, it is possible that processing some types of coarse RCA to obtain the gradation required for the AMBT produces sample with significantly less reactive aggregate, and more mortar, than those in the original coarse RCA. If this is the case, the AMBT will likely underestimate the reactivity of the original coarse RCA. Hence, the suitability of the AMBT for evaluating the reactivity of RCA should be further investigated using RCA from different sources.

Lithium nitrate has shown high efficacy in mitigating expansion due to ASR in both new and in-service concrete. One of the mechanisms suggested by Kurtis et al. [14] is that some lithium salts may prevent repolymerization of the gel. Lithium was used in this research with the idea that it would stop any further repolymerization and expansion, if any, of the existing ASR gel, and prevent the formation of new expansive gel. The recommended dose of lithium in molar ratio of $\text{Li}/(\text{Na} + \text{K})$ in the mix is in the range of 0.74 to 1.1% [12-13]. The total alkali content of the RCA was found to be 0.56% Na_2O_e . However, this value includes all the alkalis not only those available to the concrete pore solution. If we assume that all the alkalis are available, then the concrete would have around 2.2 times the alkalis load contributed by the Portland cement and added NaOH. In this case, the adequate lithium dose would be ≤ 2.2 times the recommended dose based on the alkalis from PC and NaOH. The results in Figure 9 showed that a molar ratio up to 2.2 was not enough to suppress the expansion in concrete with RCA, although the reduction in expansion was significant. The graph in Figure 9 also shows that increasing the $\text{Li}/(\text{Na} + \text{K})$ ratio beyond 1.5 did have significant benefit on mitigating the expansion. Combination of lithium nitrate and SCM are currently under investigation.

5 CONCLUSIONS

1. RCA produced from ASR-affected concrete after 12 years of site exposure was found to be as reactive as the original aggregate used in the mix which was a reactive siliceous limestone (Spratt).
2. The RCA required higher levels of SCM to mitigate the expansion than those required by the original reactive aggregates used in the old mix.
3. The concrete prism and the accelerated mortar bar tests were effective in evaluating the reactivity of RCA as well as the efficacy of SCM as preventive measures. It should be emphasized that the accelerated mortar bar test should be performed on representative samples that are prepared by adequately crushing and screening the coarse RCA. Fine RCA produced by primary crushing of concrete is less reactive than the coarse RCA and, accordingly, should not be used in mortar bars to predict the performance of coarse RCA

4. Lithium nitrate was effective in reducing the expansion of concrete containing RCA but the range of dosages presented in this study did not suppress the expansion to the allowable limit.

6 ACKNOWLEDGEMENT

This research project is funded by a grant from the Ontario Ministry of Transportation (MTO) under the Highway Infrastructure Innovation Funding Program, and a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). The financial support of both organizations is highly appreciated. Opinions expressed in this paper are those of the authors and may not necessarily reflect the views and policies of the Ministry of Transportation of Ontario.

7 REFERENCES

- [1] Gomez-Soberon, JMV (2002): Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study, *Cement and Concrete Research* (32-8): 1301-1311.
- [2] Park, T (2003): Application of construction and building debris as base and subbase materials in rigid pavement. *Journal of Transportation Engineering* (129-5): 558-563.
- [3] Rogers, CA (1987): Alkali-aggregate reactions in Ontario. In Grattan-Bellew, PE (editor): *Proceedings of the 7th International Conference on alkali-aggregate reaction in concrete*, Ottawa, Canada: 5-9, Published by Noyes, New Jersey.
- [4] Diamond, S (1981): Effects of two Danish fly ashes on alkali contents of pore solutions of cement-fly ash pastes. *Cement and Concrete Research* (11-3): 383-394.
- [5] Duchesne, J, and Berube, M-A (1994): The effectiveness of supplementary cementing materials in suppressing expansion due to ASR: another look at reaction mechanisms. Part 1: concrete expansion and portlandite depletion. *Cement and Concrete Research* (24-1): 73-82.
- [6] Shehata, MH, and Thomas, MDA (2000): The Effects of fly ash composition on the expansion of concrete due to alkali-silica reaction. *Cement and Concrete Research* (30): 1063-1072.
- [7] Shehata, MH, and Thomas, MDA (2002): Use of ternary blends containing silica fume and fly ash to suppress alkali silica reaction in concrete. *Cement and Concrete Research* (32): 341-349.
- [8] Shehata, MH, Thomas, MDA, and Bleszynski, RF (1999). The effect of fly ash composition on the chemistry of pore solution. *Cement and Concrete Research* (29): 1915-1920.
- [9] Thomas, MDA, (1996): Field studies of fly ash concrete structures containing reactive aggregates. *Magazine of Concrete Research* (48-177): 265-279.
- [10] McCoy, WJ, and Caldwell, AG, (1951): New approach in inhibiting alkali-aggregate expansion. *ACI Journal, Proceedings* (7-5): 693-706.
- [11] Diamond, S (1999): Unique response of LiNO_3 as an alkali silica reaction- preventive admixture. *Cement and Concrete Research* (29-8): 1271-1275.
- [12] Tremblay, C, Bérubé, MA, Benoit, F, Thomas, MAD, and Folliard, KJ (2007): Effectiveness of lithium-based products in concrete made with Canadian natural aggregates susceptible to alkali-silica reactivity? *ACI Materials Journal*, March-April 2007: 195-205.
- [13] Bérubé, MA, Tremblay, C, Fournier, B, Thomas, MD, and Stokes, DB (2004): Influence of lithium-based products proposed for counteracting ASR on the chemistry of pore solution and cement hydrate. *Cement and Concrete Research* (34): 1645–1660
- [14] Kurtis, K, Monteiro, P, Meyer-Ilse, W (2000): Examination of the effect of LiCl on ASR gel expansion. *Proceedings of the 11th International Conference on Alkali-Aggregate Reaction*, Quebec, pub. by CANMET, Ottawa: 51-60.
- [15] Scott IV, HC, and Gress, DL (2004): Mitigating alkali Silica reaction in recycled concrete. *ACI Special Publication*, SP 219-05: 61-76.
- [16] Rogers, C, Lane, B, Hooton, RD (2000): Outdoor exposure for validating the effectiveness of preventive measures for alkali-silica reaction, *Proceedings 11th International Conference on Alkali-Aggregate Reaction*, Quebec, pub. by CANMET, Ottawa: 743-752.
- [17] Shehata, MH (2001): The effects of fly ash and silica fume on alkali silica reaction in concrete, University of Toronto, Ph.D. Thesis: pp 321 + appendices.
- [18] Thomas, MDA and Innis, FA (1998): Effect of slag on expansion due to alkali-aggregate reaction in concrete. *ACI Materials Journal* (95-6): pp. 716.
- [19] Bleszynski R, Hooton D, Thomas M and Rogers C (2002): Durability of ternary blend concrete with silica fume and blast-furnace slag: laboratory and outdoor exposure site studies. *ACI Materials Journal* (99-5): 499-508.

[20] Carles-Gibergues, A, Cyr, M, Moisson, M, and Ringot, E (2008): A simple way to mitigate alkali-silica reaction. Materials and Structures (41) 73-83.

Table 1: Major oxide composition of the Portland cements and SCMs (%).

Sample	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O	Na ₂ O _c	TiO ₂	P ₂ O ₅	Car- bon	⁹ Fine- ness
¹ LAPC	62.41	20.12	4.43	2.80	3.01	3.60	0.44	0.27	0.56	0.23	0.13	-	
² HAPC	62.84	19.58	5.35	2.29	2.43	4.10	1.13	0.21	0.96	0.31	0.11		
³ SF	0.27	96.19	0.35	0.10	0.91	0.25	0.51	0.21	0.55	0.13	0.13	1.35	
⁴ SG	43.20	34.40	7.40	0.94	9.30	0.83	0.58	0.57	0.95	0.44	0.00	0.21	
⁵ F-LA	4.43	55.74	27.35	5.59	1.56	0.26	2.29	0.44	1.95	0.67	0.31	1.58	26.7
⁶ F-HA	6.42	61.29	16.81	4.62	2.15	1.12	0.98	3.68	4.30	0.95	0.54		
⁷ CI-LA	16.97	40.15	21.37	9.92	4.23	2.46	1.04	1.36	2.10	1.39	1.10	1.29	14.9
⁸ CH-LA	28.73	33.26	18.24	6.45	5.32	2.59	0.33	1.94	2.16	1.45	0.88		

¹LAPC: Low-Alkali GU Portland Cement
²HAPC: High-Alkali GU Portland Cement
³SF: Silica Fume
⁴SG: Slag
⁵F-LA: Fly Ash Type F (CaO < 8%) with low alkali content
⁶F-HA: Fly Ash Type F (CaO < 8%) with high alkali content
⁷Fly Ash Type CI (8 < CaO < 20%) with low alkali content
⁸Fly Ash Type CH (CaO > 20%) with low alkali content
⁹Fineness (%retained on 45- μ m sieve)

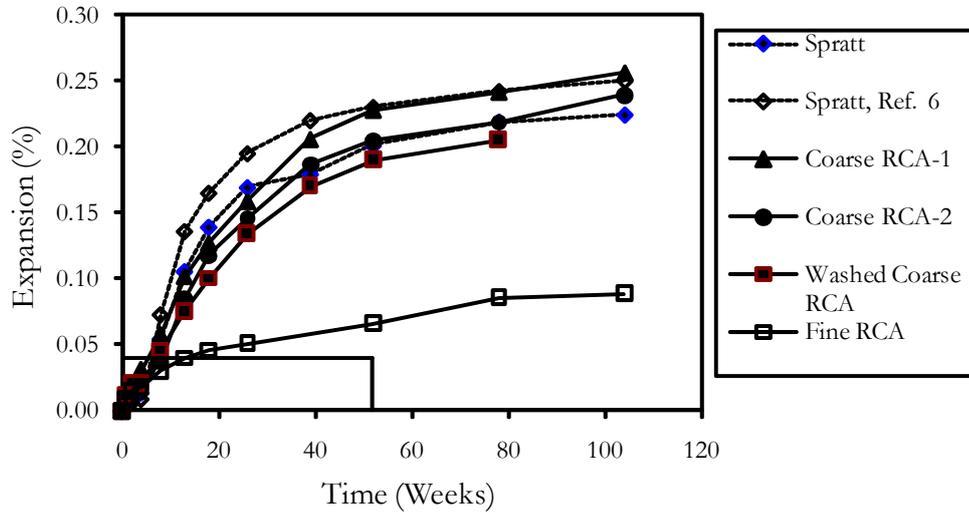


Figure 1: Expansion of control samples containing Spratt, coarse and fine RCA.

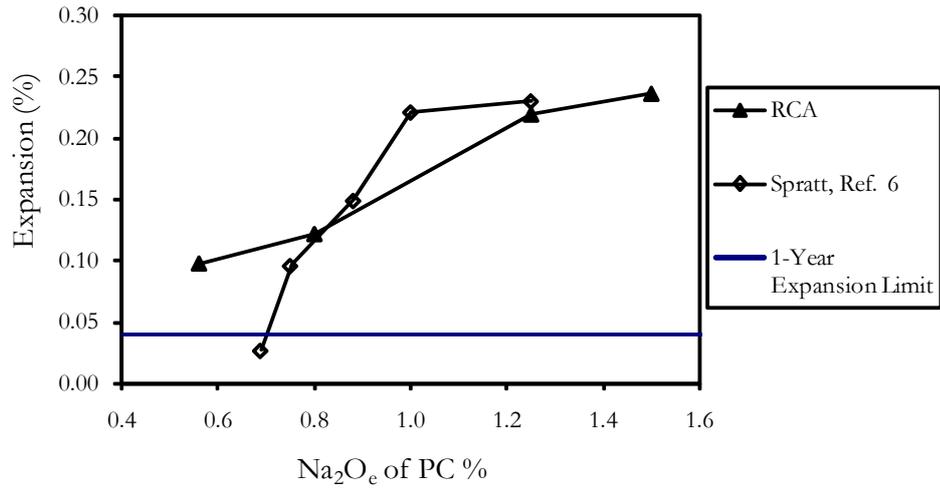


Figure 2: Effect of alkali content of PC on the one-year expansion of concrete prisms

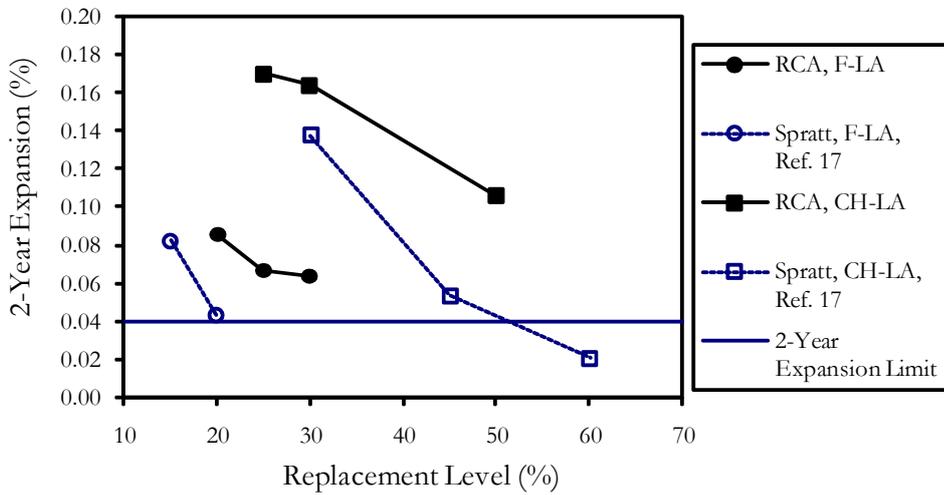


Figure 3: Effects of Types F and CH fly ash on expansion of concrete containing Spratt and RCA.

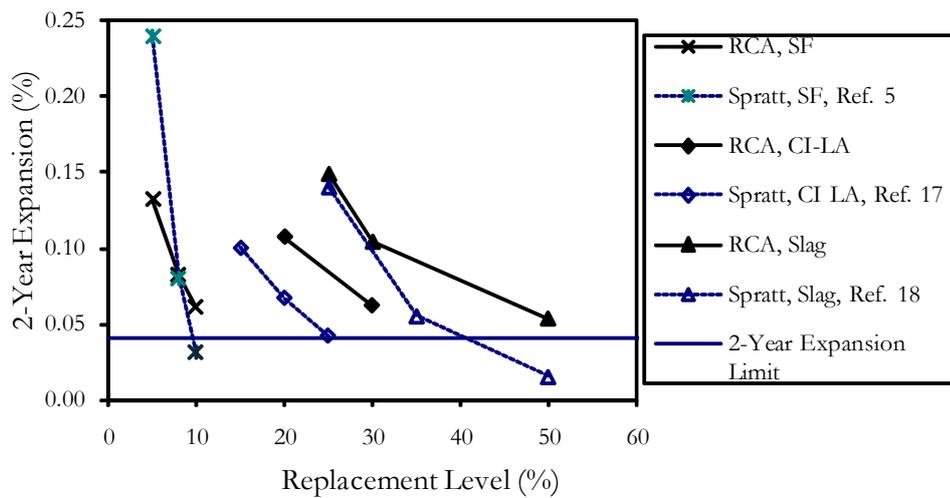


Figure 4: Effects of SF, Slag and CI FA on expansion of concrete containing Spratt and RCA.

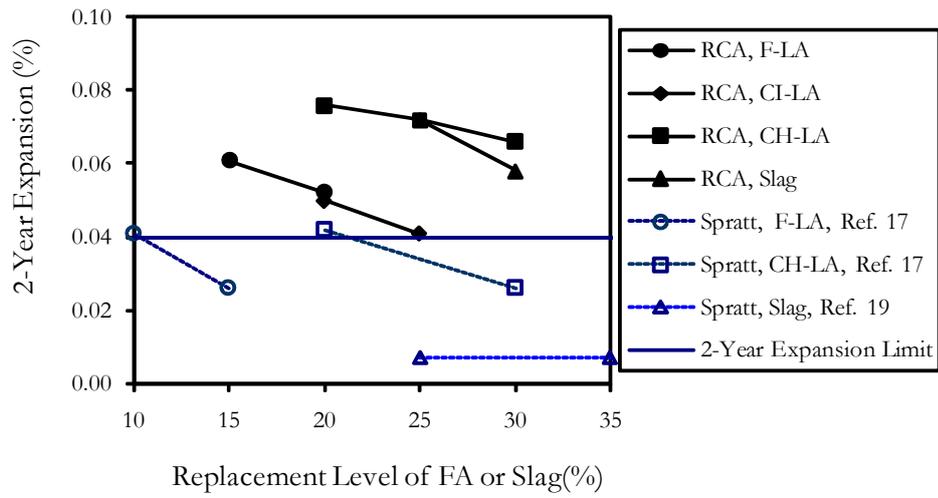


Figure 5: Expansion of concrete with ternary blends of 5% SF and different levels of FA or Slag.

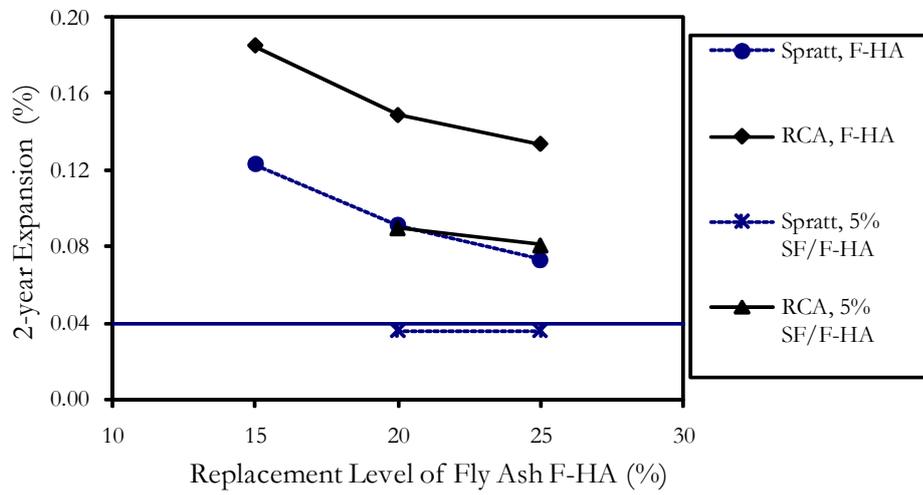


Figure 6: Expansions of concrete with ternary blends of 5% SF and different levels of FA F-HA.

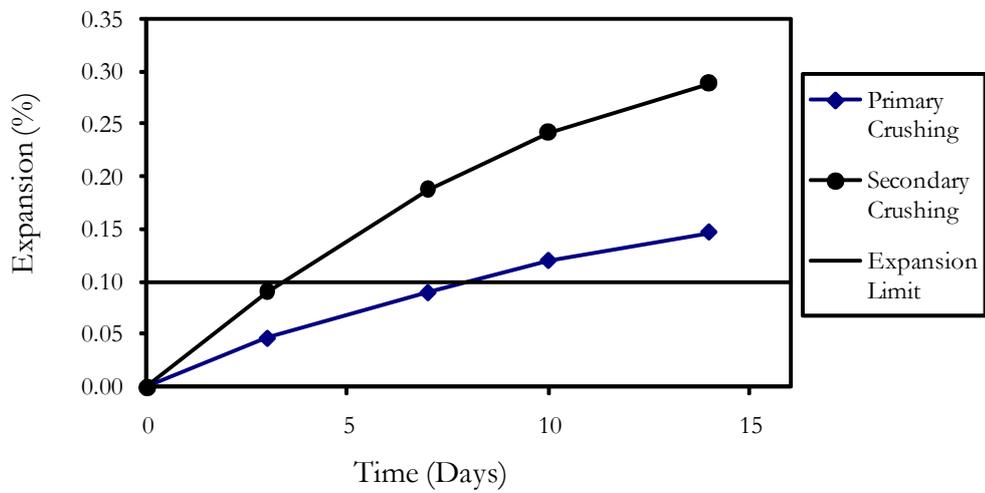


Figure 7: Expansion of mortar bars containing primary and secondary crushed RCA.

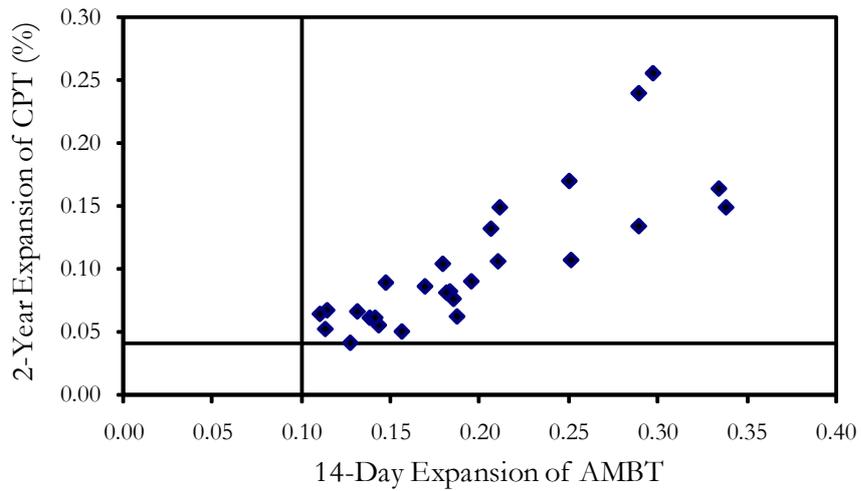


Figure 8: CPT expansion at 2 years (1 year in case of the control sample) versus 14-day expansion of AMBT for samples with RCA.

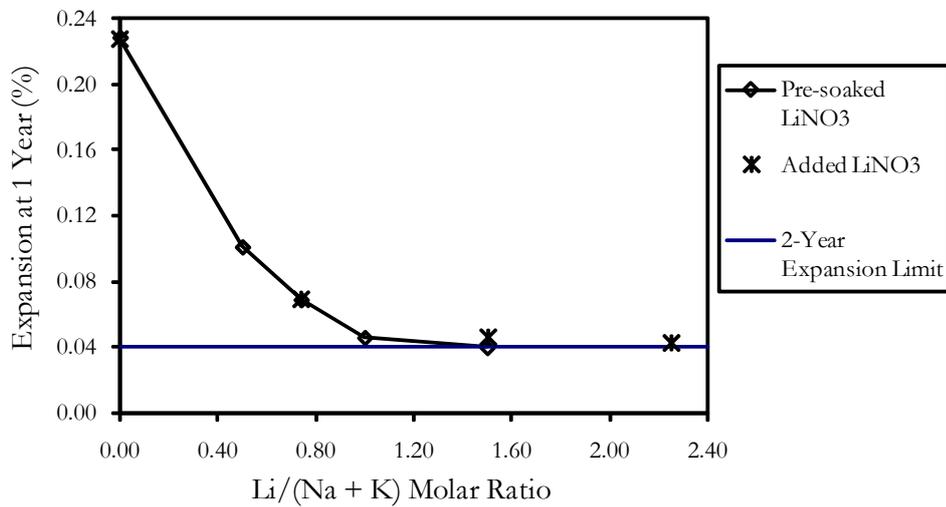


Figure 9: Effects of lithium nitrate on the expansion of concrete with RCA at 1 year.

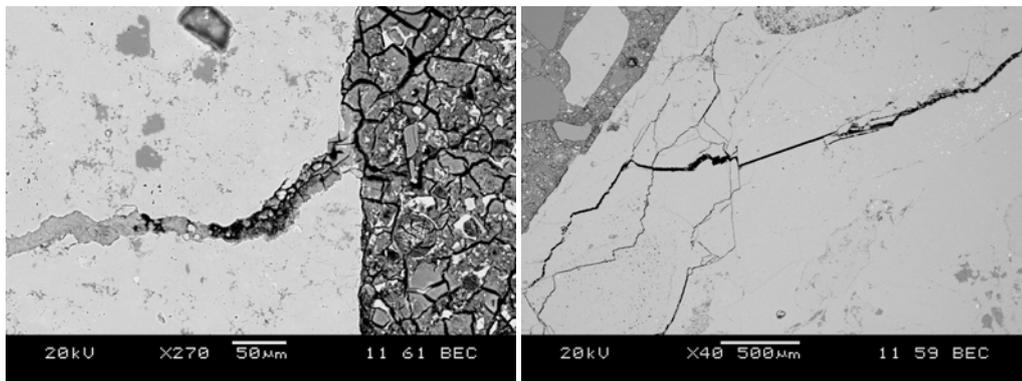


Figure 10: BSE images showing coarse RCA particles with residual pastes. Left image shows ASR-gel filled crack in the Spratt aggregate. Right image shows empty cracks in Spratt particle which is believed to be resulting from crushing and processing of the old concrete.