USE OF SCMs ON ACR-AFFECTED CONCRETE: EXPANSION AND DAMAGE EVALUATION THROUGH THE DAMAGE RATING INDEX

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Abstract

Many researches have been carried out regarding Alkali-carbonate reaction (ACR) since its discovery in the 1960s in Kingston, Ontario, Canada. In many cases, more questions than answers were arising from these investigations. Also, much debate is still occurring since some researchers have suggested, in the 1990's and recently, that ACR is a form of ASR. One of the "controversial" element of the above debate deals with the fact that the use of supplementary cementing materials (SCM), such as fly ash and slag, showed to be ineffective in controlling expansion in concrete incorporating alkali-carbonate reactive limestones, while similar preventive actions proved to control expansion with alkali-silica reactive aggregates such as the Spratt limestone. Control concrete specimens and specimens incorporating various proportions of SCMs (40% slag, 70% slag, 30% and 50% Class F Fly ash) were made in accordance with CSA A23.2-14A test 28A Standard Practice. The expansion of the above specimens was monitored over time, while some specimens were retrieved at selected expansion levels for semi-quantitative petrographic examination. As anticipated, the expansion of the Spratt limestone is suppressed by the above proportions use of SCMs at about 2 years while the Kingston limestone at similar replacement levels of SCMs was found to be largely ineffective in controlling the expansion of concrete specimens. Higher DRI values for Kingston-bearing concretes were obtained compared to Spratt-bearing concretes at similar expansion levels. Damage observed in the DRI of the Kingston-bearing concretes is characterized by much larger occurrences of cracking in the cement paste compared to Spratt-bearing concretes. The results of the modified DRI method [10] show good to very good correlations with expansion (R^2=0.99 Spratt and 0.89 Kingston). Abundant deposits of secondary reaction products, which are thought to correspond to calcite and brucite were identified in the ITZ between the Kingston aggregate particles and the cement paste, as well as within and impregnating the cement paste in the immediate vicinity of cracks extending from the reactive particles, with increasing occurrences through increasing expansion. This phenomenon related to dedolomitization suggests that it may play more than a secondary role in the expansion process of Kingston-bearing concretes.

Keywords: Alkali-carbonate reaction, SCMs, Dolomitic limestone, Dedolomitization

1 INTRODUCTION

Besides the fact that a recent review and a recent study are suggesting that ACR is obviously ASR [1-2] and some work on field concretes [3] susceptible to ACR but renowned to be ASR reactive, the current knowledge still opposes two to three main/distinct theories as an explanation for the reaction/expansion mechanism(s) in alkali-carbonate reaction (ACR). The first one, introduced half a century ago, suggests that the clay mineral *illite* disseminated in the reactive limestone, although of non-swelling-type, is responsible for the deleterious expansion. It is suggested that the *dedolomitization* of dolomite rhombs, also present in the rock matrix, is contributing to the process by opening channels/access for moisture and ionic species into the rock, thus causing expansion of the above clay mineral [1]. The second theory, introduced almost 30 years ago by Tang et al.[4], states that the reorganization of the products of *dedolomitization* results in deleterious expansion around reacting dolomite crystals in the rock matrix. In addition to the above, the last theory that was first introduced almost 20 years ago, states that ACR is only a form of alkali-silica reaction (ASR) involving cryptocrystalline quartz disseminated in the rock matrix [5-8]. Since then, many followers [1, 3, 8] have supported the idea. Nevertheless, many questions about the reaction mechanism(s) are still unsolved and need to be further investigated, as stated amongst others by [9].

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Despite that it has been extensively reported over the last 50 years that SCMs do not suppress the expansion generated by ACR below the acceptable limit of 0.04% in concrete prism test (CPT) conditions, not much data have been published on the matter except for [10]. As a consequence, research work has been carried out and data generated on that matter accompanied by petrographic characterization of the ACR and ASR affected concrete specimens. The well-known and documented Spratt (ASR reactive) limestone and the Kingston (ACR-reactive) limestone were selected and tested in this study to supplement current data on the issue with valuable insights.

2 SCOPE OF WORK

As part of a global investigative program, two reactive limestones from Canada were used in this study, i.e. the first renowned ACR-reactive Kingston limestone and the also well-documented ASR-reactive Spratt limestone, both from Ontario, Canada. CPT mixes and testing were made in accordance with CSA A23.2-14A and 28A recommendations, with expansion data being collected over a~2 year period. Test specimens were retrieved at selected expansion levels and their microstructural characteristics were determined through the *Damage Rating Index* method [11].

3 MATERIALS AND METHODS

3.1 Materials and mix designs

The ACR-reactive limestone from Kingston, Ontario is a dolomitic limestone from the Gull River formation exploited in the Pittsburg quarry ((**Pitt 16**, Kingston, retrieved by a group led P.E. Grattan-Bellew in the 1990s and stocked at CANMET [10]) (typical ACR) [12]). On the other hand, the ASR-reactive limestone is a micritic (fine-grained) limestone from the Bobcaygeon formation exploited in the Spratt quarry near Ottawa, Ontario, and was obtained from the Spratt-3 stockpile maintained by the Ontario Ministry of Transportation (MTO). CPT mixes and test specimens were made according to CSA A23.2-14A and 28A specifications and length changes were taken at selected and regular intervals. Pit-16 Kingston limestone was used as it is the most reactive layer in the first lift of the quarry and also because there is much variability in composition of the carbonate rocks in the quarry.

The Spratt and Kingston CPT mixes were designed with 30% and 50% fly ash (ASTM F type, see table 1 below for exact chemical composition and origin), 40% and 70% ground granulated blast-furnace slag (GGBFS -see table 1 below for exact chemical composition and origin), as well as control (100% portland cement) concretes. All CPT mixes were made with a high-alkali portland cement (1.11% Na_2O_{eq}), and a local non-reactive sand derived from granite. The granular material fractions used in the mixes were equal parts of 20-14mm, 14-10mm and 10-5mm for both limestones. The total cementitious materials content was maintained at 420 kg/m^3 for control and SCM-bearing mixes. A standard 0.42 water/binder was used for control and GGBFS mixes, while a 0.39 water/binder was used for fly ash mixes to account for the fluidifying effect of fly ash on slump. Reagent grade NaOH was added to all mixes in such an amount to obtain a concrete alkali content corresponding to1.25% Na_2O_{eq} by cement mass in the system.

3.2 Methods for assessment and analysis

Expansion testing

All control and SCM-bearing concretes were cast into test prisms, 75 x 75 x 300 mm in size. After 24 hours in their moulds, the prisms were demoulded, their initial length determined, and then placed at 38^{o}C and R.H. > 95%. Their length change was monitored regularly over a 104-week period.

In addition to the above, additional series of control concretes (i.e. 100% high-alkali cement) were poured into 150 x 300mm cylindrical moulds for both limestones. After 20 ± 4 hours in their moulds, the cylinders were stripped and drilled studs placed in their end portions for longitudinal length change measurements. The specimens were stored at 38^{o}C and R.H. > 95% and regular measurements were taken. Specimens were then retrieved for microstructural analysis at 0.05% expansion intervals.

The Modified DRI method [11]

The control cylinders retrieved at different expansion levels were sawed longitudinally in two and one side polished using abrasive magnetic pads (up to 3000 grit) and minimum water as a lubricant. This method ensure no or minimal polishing residues (slurry) stays in the concrete pores or cracks after final polishing.

The *Modified DRI method* is based on the original and revised DRI method by P.E. Grattan-Bellew and co-authors [13-15]. Since then, several authors used and modified the method slightly [16-20]. The *modified DRI method* [11] consists in a count, under the stereomicroscope (≈16x magnification), of the number of petrographic features of deterioration (commonly associated to ASR, Table 2, Figure 5 and 6) on polished concrete sections on which a grid is first drawn (1 by 1 cm in size)(Figure 5 and 6). The *DRI* thus represents the normalized value (to 100 cm^2) of the frequency of these features after the count of their abundance, over the surface examined, has been multiplied by weighing factors representing their relative importance in the overall deterioration process (Table 2). A minimum of 200 cm^2 were examined for each sample. The polished sections subjected to DRI measurements were thus prepared from 150mm x 300mm cylinders for control mixes and from 75 x 75 x 300 mm prisms for the SCM-bearing concretes.

4 RESULTS

4.1 Expansion of the Kingston and Spratt limestones in CPT (CSA A23.2-14A and 28A)

Figure 1 shows the expansion curves over time for both limestones and reaction types (ACR vs ASR). The dashed (blue) curves are for the Spratt limestone and thick (red) curves for the Kingston limestone. Each curve represents the mean expansion obtained from 3 prisms by mixes until retrieval of 1 prism for Kingston SCMs mixes. Therefore, the expansion of Kingston SCMs mixes is the mean of two prisms between 334 and 378 days of testing (50% FA = 334 days, 40% GGBFS = 341 days, 30% FA = 349 days and 70% GGBFS = 378 days). In fact, very similar expansions were obtained on each SCM mix prisms before retrieval of 1 prism, so it is believed that the mean was not affected significantly. The horizontal dashed (green) line is the non-reactive threshold of 0.04% expansion level.

It can be seen from the plot that all Spratt + SCMs mixes are still below the 0.04% expansion limit at 700 days. The Spratt control mix is, as expected, very reactive at almost 0.24% expansion at ~2 years. The Kingston control mix is at approximately 0.68% expansion at over 800 days, which is about 3 times the expansion of the Spratt limestone at similar age.

The Kingston + SCMs mixes show a different trend, where the curves are slightly "shifted" to the right of the plot (compared to the control), thus showing that the rate of expansion is somewhat slower in the early stage. However, the Kingston + SCMs prisms eventually expanded more than the control specimens (i.e. 30% and 50% FA, and possibly 40% GGBFS in a near future). For Kingston 70% GGBFS, it seems that the above dosage limits greatly the expansion compared to the control specimens and other SCM mixes but, still, the expansion is well over the 0.04% limit and near the expansion of the Spratt control mix.

3.1 DRI on the selected samples

The bar charts in Figures 2 show the different proportions of the damage features and the DRI values associated to each sample tested (Kingston [ACR] and Spratt [ASR], respectively). For the Kingston samples with SCMs, similar expansion levels were chosen to perform the DRI, i.e. ~0.35% expansion. No sample with SCMs was tested for Spratt limestone, as no significant ASR reaction occurred (<0.04% expansion).

When comparing Spratt and Kingston in Figure 2, it can be seen that with increasing expansion in the control specimens, much more cracks are present in the cement paste (CrCP and Cr+RPCP) for Kingston compared to Spratt at similar expansion. Other damage features seem to be in similar numbers, except that there is several debondings in Kingston limestone compared to none for Spratt limestone. Moreover, most of the cracks within Kingston coarse aggregate particles were originating from the border of the particles compared to Spratt that were more of random origins but mainly from the center of the particles (or passing through) (sharp cracks in [12]).

Figures 2 also show that the DRI values increase steadily with the expansion attained for both Spratt and Kingston limestones. However, DRI values for Kingston limestone are significantly larger than those of Spratt limestone for similar expansion levels. It seems, from the data shown in the above figures, that the Kingston + SCMs mixes DRI values are globally similar to that of the control specimens with similar expansion levels but with lower occurrences of damage in the cement paste. However, the 30% FA mix is well over the Kingston 0.500% expansion control specimen for almost all damage features including the DRI value.

Figure 3 shows the correlation between DRI value and expansion for both Kingston (a) and Spratt limestones (b). The correlation (linear regression in purple) is very good for Spratt (R^2=0.99) and quite good for Kingston limestone (R^2=0.89).

Examples of the damage features identified in the test specimens are shown in Figure 4 (Spratt) and 5 (Kingston). Figure 4 shows typical features associated to ASR in many aggregate types. Reaction products in Figure 4 are most probably ASR silica gel. Figure 5 shows typical features associated to ACR (Kingston limestone). The emphasis below is given on three features identified with increasing occurrences as the expansion is increasing in the control and SCMs samples. The first one, which corresponds to a yellowish calcite rim (and maybe brucite also) in the cement paste (CRCP) (see Figure 5), is not a commonly reported damage feature in the literature as it is not even counted in the standard [14-16] or in the modified DRI method [11]. The second are cracks in the cement paste with reaction products (Cr+RPCP) that are more yellowish (within and in the immediate vicinity of the cracks) than the glassy/whitish typical ASR gel. The width of the "impregnated" zone within the cement paste besides cracks increases with increasing expansion. The last feature is the reaction products lining in the voids, which seems to correspond to calcite rhombs instead of typical ASR gel, especially when cracks pass through the void.

5 DISCUSSION

Figure 1 shows that there is definitely a huge difference between the expansion curves for the concrete specimens incorporating the Spratt (ASR) and the Kingston (ACR) limestones, not only in terms of the total expansion reached over time but also regarding the rate of expansion. The control Spratt limestone concrete curve seems to level off at about 2 years and the expansion potential is suppressed by the various dosages of the SCMs used in the study. The expansion curves of the Kingston limestone SCM-bearing mixes, as mentioned above, are all way over the Spratt control curve, except for the 70% GGBFS (but it should be over it shortly), and some are actually over the Kingston limestone control at 800 days. This means that the mechanisms responsible for limiting/suppressing the expansion for ASR reactive rocks (pH reduction in the pore solution, alkali dilution through cement replacement, reduction of concrete permeability, and consumption of $Ca(OH)_2$ through pozzolanic reactions [22]) do not work for the Kingston limestone. In fact, the expansion for Kingston + SCM specimens is sustained longer compared to the Kingston control specimens, probably through denser/less permeable hardened cement paste [23] and, as a consequence, lower leaching of alkalis in the test. This, in addition to other data/reasons mentioned amongst others by [9], suggest that there is in fact different mechanisms than solely ASR, responsible (or partly responsible) for the huge expansive reaction. In fact, there is ASR playing a role [24 and 5-8] in the reaction mechanism, as it has been observed in another study [23] (amongst others), as well as in this research work. It is suggested that a combination of reaction mechanisms (other mechanism + ASR as a secondary reaction) would be responsible for the renowned deleterious expansion generated by the alkali "carbonate" reactive Kingston limestone [24 in prep.].

There is an increased occurrence of cracks in the cement paste (CrCP and Cr+RPCP) and debondings (CAD) (Figure 2) in Kingston limestone concretes compared to Spratt limestone concretes of similar expansion levels. This suggests that there is possibly much more reaction occurring near the border of the Kingston aggregate particles and the cement paste (ITZ) [12] than from the interior (center) of those coarse aggregate particles that then extend into the paste. The higher DRI values obtained for Kingston concretes compared to Spratt concretes of similar expansions is related mainly to the weighing factors that are higher for damage features in the cement paste to increase the relative damage in the method (as cracks in the paste governs the overall damage of concrete). In other words, a larger number of counts of *cracks in the cement paste (with or without reaction products)* for the Kingston concretes compared to the Spratt concretes, at similar expansion levels, results in significantly higher DRI values for the former. In the Spratt limestone examinations, Cr+RPCA and Cr+RPCP were attributed to silica gel but in Kingston limestone examinations, they were attributed to about 75% calcite and 25% silica gel.

It was found that the modified DRI method [11] correlates well with the expansion generated by both types of limestones, with good to very good correlations (R^2=0.99 Spratt and 0.89 Kingston). However, there are still some behaviours under investigations; for example, the DRI value (and damage feature occurrences) obtained for the 30% FA (0.405% expansion) mix is much higher than the one from the Kingston control at 0.500% expansion.

For the Kingston control and SCM specimens, the emphasis was given on the following three damage features observed in the DRI evaluations: 1) the yellowish products in the interfacial zone between the aggregate particles and the cement paste which was also observed by [25] in thin sections and [26] at the SEM, 2) the voids lined with possible calcite rhombs, and 3) the presence of calcite (and possibly brucite) filling cracks and impregnating the cement paste in the vicinity of those cracks also observed by [25-26]. The fact that the extent of the above features, likely resulting from the dedolomitization process, increases with increasing expansion suggests that this phenomenon actually plays a significant role in the overall reaction mechanism and perhaps in the expansion process of the Kingston aggregate bearing concretes, as stated by [4]. This phenomenon was also observed in thin sections, as illustrated in Figure 6, which is described in details in [24 in prep.].

6 CONCLUSIONS

The present contribution aims at documenting the fact that the use of SCMs does not suppress/limit the expansion mechanism of ACR reactive rocks, especially the Kingston renowned dolomitic limestone. Semi-quantitative petrographic analyses were performed using the Damage rating Index (DRI) method, on concrete specimens of increasing expansions levels and incorporating both the Spratt and the Kingston limestones, as well as on Kingston + SCMs specimens. Considering what was presented above, it can be concluded that:

- The expansion of the control concrete specimens incorporating the Spratt limestone seems to level off at about 2 years (0.24% expansion), and the expansion potential is suppressed by the use of SCMs (e.g. 30 and 50% class F fly ash; 40 and 70% slag).The same replacement levels are ineffective for Kingston limestone concrete.
- Increased occurrences of cracks in the cement paste (with and without secondary products) and debondings (CAD) for Kingston limestone control concretes compared to Spratt limestone control concrete, at similar expansion levels, show that there is possibly much more reaction occurring near the border of the Kingston aggregate particles and the paste (ITZ).
- The higher DRI values for Kingston-bearing concretes, at similar expansion levels, are related mainly to the weighing factors in the DRI method that are higher for cracks in the cement paste (3) compared to cracks in aggregate particles (2). It thus emphasizes the previous point. The results of the modified DRI method [10] show good to very good correlations with expansion of the concrete incorporating both reactive limestones selected for this study (R^2=0.99 Spratt and 0.89 Kingston).
- Abundant deposits of secondary reaction products, which are thought to correspond to calcite and brucite were identified in the Kingston bearing concrete. The fact that increasing occurrences of the above features were found with increasing concrete prism expansion suggests that this phenomenon, likely related to dedolomitization, may play more than a secondary role in the expansion process of Kingston-bearing concretes, as stated amongst others by [3].

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TABLE 1: Chemical composition and physical properties of the SCMs used in this study.

Chemical composition (% mass)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Cr_2O_3	LOI	Total	Na_2O_{eq} (alkalis)	Density
Fly ash (Brunner Island)	47.5	24.4	15.3	0.92	4.36	0.94	1.74	1.21	0.03	0.39	0.02	3.27	96.8	2.08	2.63
GGBFS (Camden)	35.5	12.0	0.39	7.36	41.5	0.31	0.39	0.50	0.37	0.02	0.01	0.34	98.4	0.57	2.97

TABLE 2: Petrographic features and weighing factors [10].

Measured feature	Abbreviation	Weighting Factor
Closed/tight crack in coarse aggregate particle	CrCA	0.25
Opened crack or network cracks in coarse aggregate particle	OCrCA	2
Crack or network cracks in coarse aggregate with reaction product	Cr+RPCA	2
Crack in cement paste	CrCP	3
Crack in cement paste with reaction product	Cr+RPCP	3
Coarse aggregate debonded	CAD	3

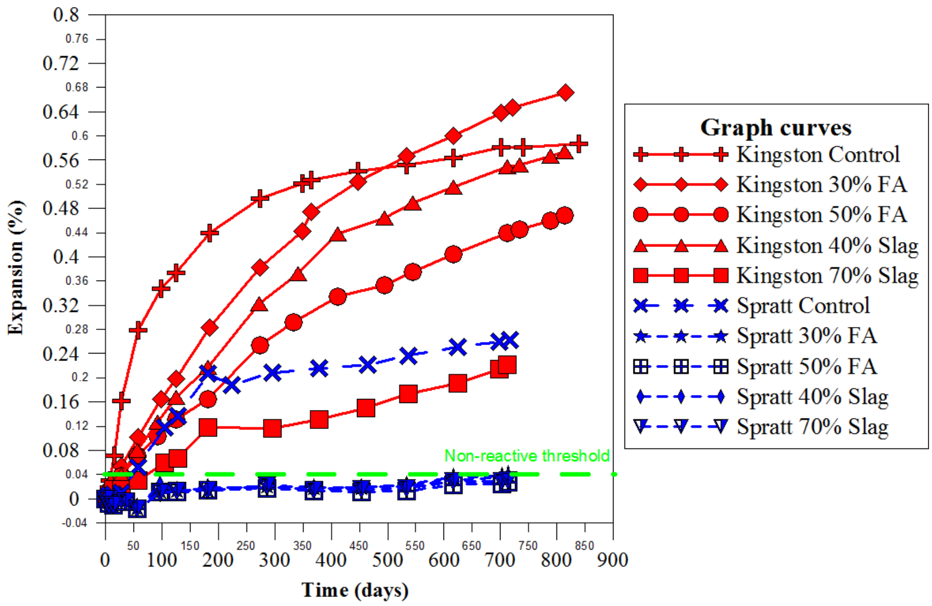

FIGURE 1: Expansion (%) as a function of time for concrete specimens made in accordance with CSA A23.2-14A and 28A, and incorporating Kingston and Spratt reactive limestones (control, with fly ash (FA) or ground granulated blast-furnace slag (GGBFS)).

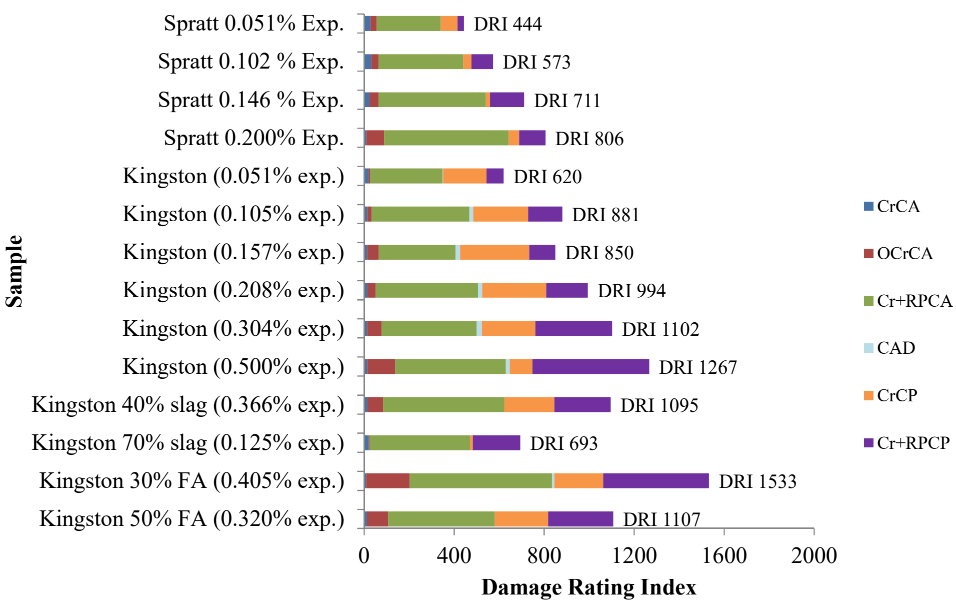

FIGURE 2: Detailed DRI results with corresponding expansion (%) of the test prisms and concrete formulations incorporating the Kingston and Spratt limestone.

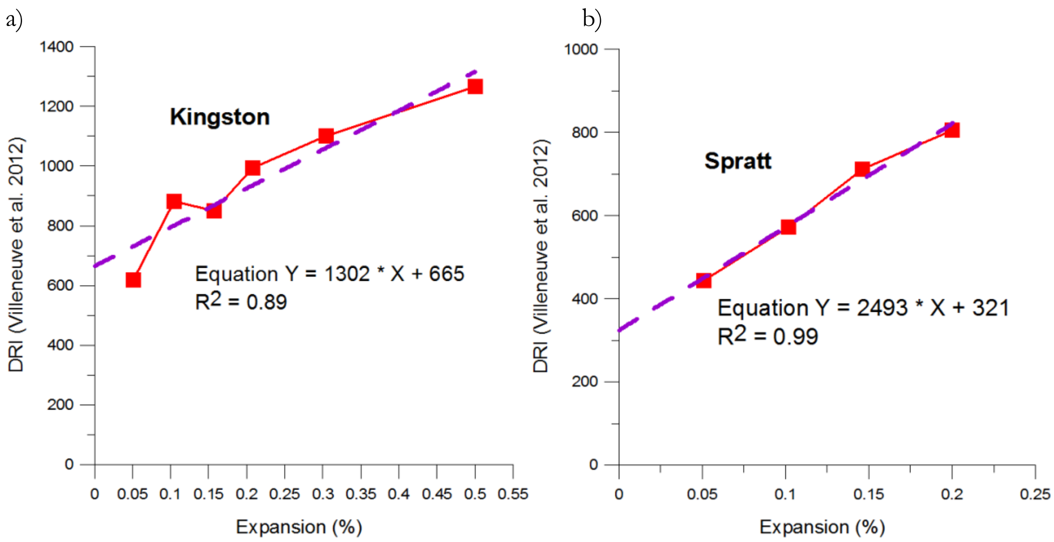

FIGURE 3: Correlation between DRI [10] and expansion (%) for control concrete specimens incorporating a) Kingston limestone and b) Spratt limestone.

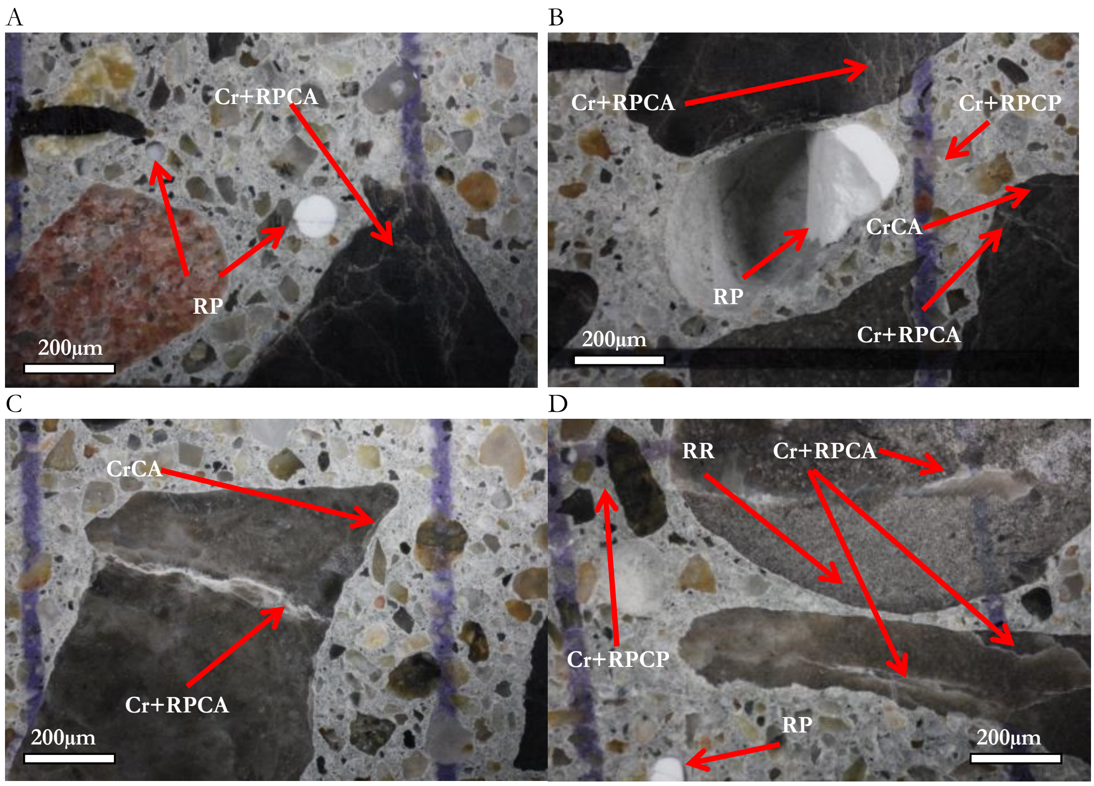

FIGURE 4: Petrographic features of ASR in Spratt limestone concrete at 0.20% expansion in CPT conditions; A: A crack in a coarse aggregate particle with reaction products (silica gel) (Cr+RPCA)and 2 voids filled with reaction products (silica gel) (RP); B: Numerous cracks in coarse aggregate particles with reaction products (silica gel) (Cr+RPCA), a closed crack in a coarse aggregate particle (CrCA), a crack in the cement paste filled with reaction products (silica gel) (Cr+RPCP) and a void partially filled with reaction products (silica gel)(RP); C: A crack in a coarse aggregate particle with reaction products (silica gel) (Cr+RPCA) and a closed crack in a coarse aggregate particle (CrCA); D: Numerous cracks in coarse aggregate particles with reaction products (silica gel) (Cr+RPCA), a crack in the cement paste filled with reaction products (silica gel) (Cr+RPCP), a reaction rim at the interior edge of a coarse aggregate particle (RR) and a void filled with reaction products (silica gel)(RP).

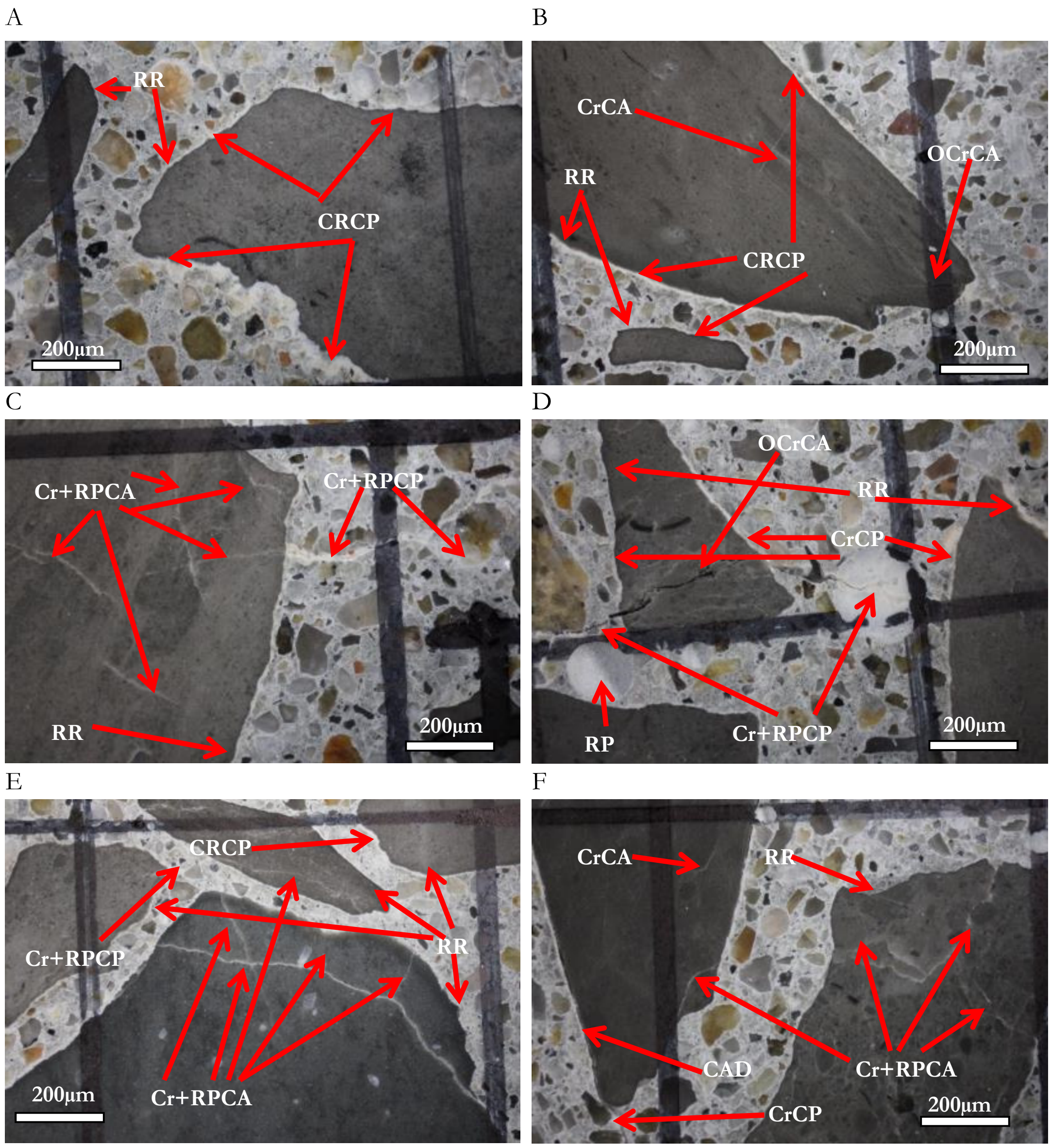

FIGURE 5: Petrographic features of ACR in Kingston limestone concrete at 0.50% expansion in CPT conditions A: Reaction rims at the interior edge of two coarse aggregate particles (RR) and a white/yellowish calcite rim in the cement paste at the exterior edge of a coarse aggregate particle (CRCP); B: An opened crack in a coarse aggregate particle (OCrCA), a closed crack in a coarse aggregate particle (CrCA), reaction rims at the interior edge of two coarse aggregate particles (RR) and a white/yellowish calcite rim in cement paste at the exterior edge of a coarse aggregate particle (CRCP); C: Numerous cracks in a coarse aggregate particle with reaction products (Cr+RPCA), a crack in the cement paste with reaction products (Cr+RPCP) and a reaction rim at the interior edge of a coarse aggregate particle (RR); D: An opened crack in a coarse aggregate particle (OCrCA, reaction rims at the interior edge of two coarse aggregate particles (RR), white/yellowish calcite rims in the cement paste at the exterior edge of two coarse aggregate particles (CRCP), a void lined with reaction products (RP) and two cracks in the cement paste with reaction products (Cr+RPCP); E: Reaction rims at the interior edge of several coarse aggregate particles (RR), numerous cracks in a coarse aggregate particle with reaction products (Cr+RPCA), two crack in the cement paste with reaction products (Cr+RPCP) and a white/yellowish calcite rim in the cement paste at the exterior edge of a coarse aggregate particle (CRCP); F: A closed crack in a coarse aggregate particle (CrCA), a reaction rim at the interior edge of a coarse aggregate particle (RR), a debonded coarse aggregate particle (CAD), numerous cracks in a coarse aggregate particle with reaction products (Cr+RPCA) and a crack in the cement paste (CrCP).

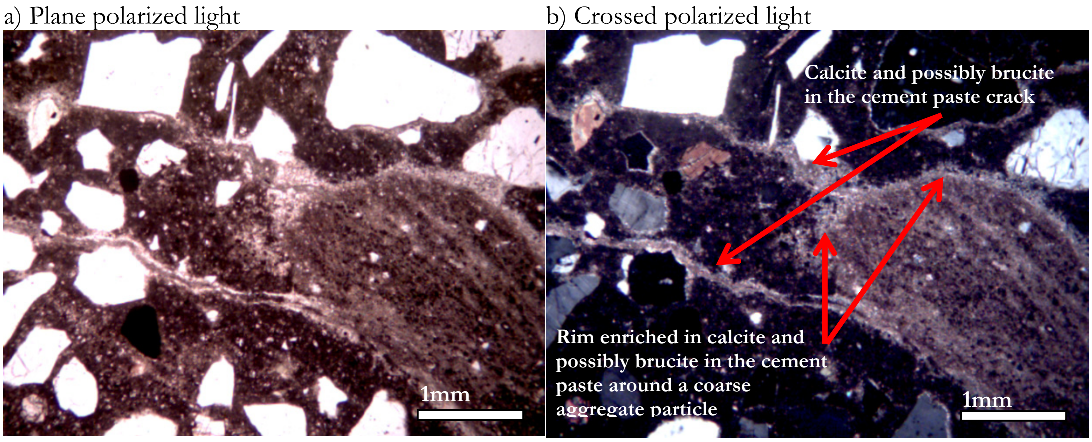

FIGURE 6: Pictures in plane polarized and crossed polarized light at 40x of Kingston limestone (ACR) concrete at 0.500% expansion in CPT conditions; a) picture in plane polarized light showing two cracks in the cement paste filled with reaction products originating from a coarse aggregate particle and a rim in the paste around a coarse aggregate particle, b) picture (crossed polarized light)of the same location showing two cracks in the cement paste filled with calcite and possibly brucite originating from a coarse aggregate particle and a calcite and possibly brucite rim in the cement paste around a coarse aggregate particle.