PETROGRAPHIC ANALYSIS OF AGGREGATE PARTICLES USED IN THE ACCELERATED MORTAR BAR TEST FOR EVALUATING THE POTENTIAL ALKALI-REACTIVITY OF RECYCLED CONCRETE AGGREGATES (RCA)

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Abstract

An image analysis method was employed in an interlab study [1] on recycled concrete aggregate (RCA). The accelerated mortar bar test (AMBT) used in this study has shown significant expansions differences after 14 and 28 days between two fine aggregate types of RCA prepared from concrete blocks or coarse RCA particles affected by alkali-silica reaction (ASR). The petrographic analysis (by image analysis) carried out on the two different types of fine aggregates detected a difference in the composition characteristics of the aggregate produced from the primary crushing of the concrete blocks (*crusher's fines),* which are mainly composed of residual mortar (RM), compared to the *crushed RCA*, resulting from the re-crushing of coarse RCA particles (5 to 20 mm). Therefore, this difference will initiate a greater ASR potential in mortar bars made of *crushed RCA* because of the higher proportion of reactive original virgin aggregate particles (OVA). Consequently, the method used for the fine aggregate used in the fabrication of mortar bars has a significant impact on the material's composition and so on that undergoes higher expansion of mortar bars.

Keywords: Recycled concrete aggregate (RCA), *crusher's fines*, *crushed RCA*, alkali-silica reaction (ASR)

1 INTRODUCTION

Recycling is becoming a more integral part of society and is widely encouraged. In recent years, there has been a growing interest in the construction sector to consider the possibility of reusing materials resulting from the demolition of concrete infrastructures that have reached their life expectancy as aggregate for new concrete. Although this has become accepted in certain parts of the world, numerous issues remain about the long-term performance (durability) of concrete incorporating recycled concrete aggregates (RCA); many of them are indeed affected by various pathologies, such as an alkali-silica reaction. A recent interlaboratory study was carried out for verifying whether the accelerated mortar bar method (AMBT) ASTM C 1260 used for assessing the potential alkali-silica reactivity of concrete aggregates could also be appropriate for RCA incorporating various types of OVA [1]. This was prompted by the results of a previous study reported by Shehata et al. [2] for RCA incorporating the highly-reactive Spratt limestone. However, the latter demonstrated that the expansion that may deleteriously affect mortar samples depends on its production method, even if it is composed of the same original virgin aggregate (OVA).

2 SCOPE OF WORK

In this study, the AMBT was used on RCA incorporating four different types of reactive OVA: Alberta gravel (AG), Bernier limestone (BL), Potsdam sandstone (PS) and Springhill greywacke (SG) [1]. Two types of fine aggregate materials, resulting from different processing methods, have also been used to produce the aggregate for the AMBT, i.e. *crusher's fines* and *crushed RCA*. In fact, the *crusher's fines* correspond to the fine aggregate (< 5 mm) produced from the primary preparation of the RCA (from demolition blocks). On the other hand, the *crushed RCA* is the fine material (also < 5 mm) used to evaluate the alkali-silica potential of the coarse RCA, and obtained in the laboratory following the processing operations normally used for preparing material from coarse aggregates in the ASTM C 1260 method. The expansion tests on mortar revealed considerable differences between the two types of samples (Figure 1)[1]. Indeed, the mortar bars incorporating AG and SG showed significantly higher expansions with the *crushed RCA* than with *crusher's fines*. On the other hand, RCA's incorporating the BL and PS also offered expansion differences, but at a much lower level. In order to explain this difference in the behavior between the *crusher's fines* and the *crushed RCA* [1], petrographic examination of the materials incorporating the AG and the SG, which provided the highest difference between the two production methods, was done by image analysis. The objective of this analysis was to compare the proportions of the OVA and the residual mortar (RM) in both fine materials. Indeed, we hypothesized that the *crusher's fines* would include a higher proportion of RM than the *crushed RCA*, thus potentially explaining the lower expansions obtained for the former material in the AMBT [1].

3 MATERIALS AND METHODS

3.1 Aggregate Materials and Block Specimens

Both types of the fine aggregate materials used for the mortar bar testing and the petrographic examination came from the crushing of concrete blocks that have been subjected to natural environmental conditions at the CANMET outdoor exposure site located in Ottawa (ON, Canada) (figure 2) [2,3]. Those blocks, 400 x 400 x 700 mm in size, were placed outdoors more or less 15 years ago for evaluating the alkali-reactivity potential of a variety of reactive aggregates [3,4]. Thus, two to five blocks incorporating four different reactive aggregates (AG, BL, PS and SG) have been crushed in order to produce the RCA. The ultimate expansions values obtained for these blocks are presented in Table 1.

3.2 Aggregate Processing Operations

The Figure 3 illustrates the processing operations that were used to produce the recycled concrete aggregate materials for ASR testing in mortar and concrete. The concrete blocks were first broken with a jackhammer to produce particles of ≤ 200 mm in size. The material was then introduced into a swinghammer crusher, which allowed reducing the material to ≤ 25 mm. The material was then sieved on a Gilson screening machine and the following size fractions were recovered: -20+14 mm, -14+10 mm, -10+5 mm, -5 mm (*Crusher's Fines*) (Figure 4). The +20 mm aggregate material was sent again through the swinghammer crusher until all material passes the 20 mm sieve.

Representative 10-kg samples of the four RCAs, which were composed of equal quantities of the main RCA size fractions (-20+14 mm, -14+10 mm, -10+5 mm), were then collected by quartering and sent to the four laboratories involved in the interlaboratory study [1], where they were crushed and sieved by local personnel to produce the different size fractions required for mortar testing, i.e. 4.75 - 2.36 mm, 2.36 - 1.18 mm, 1.18 - 0.63 mm, 0.63 - 0.30 mm, 0.30 - 0.15mm (Cr*ushed RCA)*. Representative samples of the four *Crusher's fines* were also obtained by quartering and supplied to the participating laboratories where they were sieved and used in the mortar bar testing program [1].

3.3 Petrographic Examination of the *Crusher's fines* and *Crushed RCA*

3.3.1 Thin sections preparation

In order to perform the quantitative petrographic examination of the fine RCA materials, thin sections were made of each of the five mortar size fractions described before (for both the *crusher's fines* and *crushed RCA)*. In order to do so, a flexible silicon-based mold, 50 by 75 mm in size, is filled with RCA particles of each of the size fractions. The mold is then filled with epoxy resin to produce a "cookie". After 24 hours, the cookie is cut in its middle portion (parallel to the surface) using a diamond-saw. One of the two sawn surface thus obtained is then glued onto a glass plate and the cookie is then cut and gradually thinned to 30 microns thickness using a grinding machine. Finally, the sections were covered with varnish to protect the sample.

3.4 Image Analysis

In order to analyze the composition of the fine aggregate particles (i.e. determine the proportions of RM and OVA in each fine aggregate particle), a series of micrograph were made. The photos were then imported into ArcGIS, a software package that is commonly used by geoscientists to produce different types of maps. A mosaic was then produced with a collection of photos for each size fraction, using a georeferencing process (common points on each photo). Using this method allows the software to create one single mosaic by pasting all photos according to their common points, until one large picture is obtained; incorporating at least 300 particles of each size fraction, as recommended by CSA A23.2-15A.

The final step consists in the image segmentation (Figure 6). The software includes a feature that allows the user to separate the RM from the OVA. This function consists in adding a "working layer" over the mosaic so that the operator can trace the outline of each material type with a digital pen, for instance the RM and the OVA fractions of the RCA particles. Once completed, the software can easily calculate the area occupied by each type of materials and a simple calculation will reveal the relative proportion of RM for each analyzed particle. The software also allows determining the area occupied by each particle on the thin section; this makes the RM proportion calculation much easier.

4. RESULTS

4.1 Expansion of the mortar bars

As mentioned before, the results of the interlaboratory study highlighted a significant difference in the expansive behavior of the *crushed RCA* (higher expansions) and the *crusher's fines* materials incorporating both the AG and SG, while the difference was much less evident between the two sets of bars made with the PS and BL (Figure 1)[1]. It should be noted that after 14 days, the expansion of the reference mortar bars made of those two types of aggregates (PS: 0.093%; BL: 0.173%) was significantly lower than that obtained for the bars made with SG (0.463%) et AG (0.360%) (Figure 1).

4.2 Petrographic examination

Table 2 and Figure 5 show the total residual mortar content (RMC %) included in at least 300 particles of each size fraction examined for the *crushed RCA* incorporating the SG and AG aggregates. The RMC (%) has been calculated by using the measured areas (by image analysis) of the residual mortar (RM) and the original virgin aggregates (OVA), the materials bulk specific gravities (SG_B) (SG_B for the residual mortar = 1.8 [6]; SG_B for the aggregate AG = 2.61; SG_B for the aggregate SG = 2.70) and an infinitesimal thickness, as suggested by Abbas et al. 2007 [5] and Gholamreza [6]. The trend shows that the smaller the size fraction is, the greater the RMC (%) will be. On the other hand, Table 3 and Figure 5 show the RMC (%) included in 300 particles of each size fractions examined for the *crusher's fines* incorporating the SG and AG aggregates. The trend shows this time that the RMC (%) increases with increasing particle size of the aggregate material.

Figure 7 illustrates the amount of particles with a specific RMC (between 0 and 100%, in increments of 10%) for each size fraction of both types of fine aggregates incorporating the SG aggregate. We observe on those figures that all size fractions, for both the *crusher's fines* and the *crushed RCA*, are most exclusively composed of particles with few (0-10%) or much (90-100%) RM, intermediate mixtures are rarely observed. The results presented in the Figure 7 (*crushed RCA*) show that the proportion of particles incorporating 0-10% RM varies between 37.7% and 61.5%, with values gradually decreasing with decreasing particle size. The percentage of particles incorporating from 90-100% RM varies between 32.9% and 51.5%, with values generally increasing with decreasing particle size. Regarding the *crusher's fines* (also in Figure 7), the proportion of RCA particles that contain 90-100% RM ranges from 47.5% to 62.9% for the various fraction sizes examined, which is largely more than those containing a small proportion of RM (0-10%; from 27.9% to 40.9% for the various size fractions examined).

The graphs of Figure 7 indicate the amount of particles incorporating a specific percentage of RM (between 0 and 100%, in increments of 10%), for each size fraction of both types of fine aggregates incorporating the AG aggregate. Similar to the fine aggregates incorporating the SG aggregate, the particles in all size fractions of the two types of fine aggregates (*crusher's fines* and *crushed RCA*) are largely made of a few (0-10%) or much (90-100%) RM, with rare intermediate mixtures being observed. In the case of the *crushed RCA,* the proportions of particles incorporating 0-10% RM (39.0-52.3%) or 90-100% RM (33.1--55.6%) are quite similar, on an average. On the other hand, the *crusher's fines* contain a much larger proportion of particles containing a large amount of RM (90-100%: 47.5% to 62.9%) compared to those with small amounts of RM (0-10%: 35.4% to 40.9%).

The typical differences in the proportions of RM between the *crusher's fines* and the *crushed RCA*, for granular materials incorporating the AG and SG aggregates, can be seen in the Figures 8A to 8D for particles of the 16-30 mesh (1.18 - 0.63 mm) size fraction.

5. DISCUSSION

The amount of aggregate susceptible to trigger expansion due to ASR in a mortar or concrete mixture was determined. For RCA, a high proportion of RM in the RCA material is likely to reduce the intensity of the ASR expansion (at least for reactive aggregate material not susceptible to a pessimum effect), if we consider that the silica gel present in the RM porosity contributes less to the future growth than the OVA fragments. This is plausible considering that the silica gel present in the cement paste is generally richer in calcium and relatively less expansive than the gel located within or close to the reactive aggregate particles.

According to the petrographic observations carried out in this project , the mortar bars incorporating materials obtained from the primary demolition process of the concrete blocks (*crusher's fines*) include a significantly higher proportion of RM (RM-rich particles with 90-100% RM) than in the case of *crushed RCA* type material, for both aggregates studied (AG and SG) (Figures 4-8). On the other hand, there is a much higher proportion of OVA fragments available to trigger ASR in the *crushed RCA* material, thus resulting in higher mortar bar expansions. These results are easily noticeable in the Tables 2 and 3. Indeed, the total values of the RMC for the *crusher's fines* are much higher (69.7% to 73.0% for AG and SG, respectively) than for the *crushed RCA* (52.1% to 33.8% for AG and SG, respectively).

The reason why the *crushed RCA* consist in a much higher proportion of OVA could be explained by the fact that their production requires a re-crushing that help in breaking the bonds between the cement paste and the OVA, thus helping in breaking OVA and then exposing fresh aggregate surfaces contributing to ASR expansion. The recrushing in the case of the crushed RCA likely also increases the loss of residual mortar in the dust (material < 0.15 mm).

6. CONCLUSION

The quantitative petrographic examination using image analysis, has provided critical information for understanding the differences in the expansive behavior of two types of fine recycled aggregate materials used in the manufacture of mortar bars (for AMBT). The results showed that the *crushers fines*, recovered after the primary crushing of the concrete blocks, have a much higher proportion of residual mortar-rich particles than the *crushed RCA*, obtained from the re-crushing of coarse RCA (5 – 20 mm). Therefore, this difference in composition is believed to be responsible for the difference in the expansions obtained. It appears that the fine RCA aggregate production method has a significant impact on the nature of the materials and consequently on the expansion that the mortar bars may suffer, under the influence of the ASR.

Concrete prism testing is in progress that will bring additional data for validating the AMBT results; however, it is expected that the *crushed RCA* will likely provide a more accurate indication of the potential alkali-reactivity of coarse RCA, as observed by Shehata et al. [2]. On the other hand, the AMBT may provide a reasonable indication of the *crusher's fines* material that could potentially be used as fine aggregate in concrete.

7. REFERENCES

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TABLE 1: Expansion reached by the exposure blocks when they were crushed to produce RCA.

Block Identification	Age of blocks	Range of expansion of the blocks	Average expansion (number of blocks)
AG	14 years	0.210 - 0.305%	0.263% (5)
SG	16 years	0.423 - 0.537%	0.480% (2)
BL	14 years	0.142 - 0.183%	0.162% (5)
PS	14 years	0.066 - 0.145%	0.092% (5)

TABLE 2: Composition of each of the size fractions of the *crushed RCA.* (AG: Alberta gravel; SG: Springhill greywacke; RM: Residual mortar; OVA: Original virgin aggregate; RMC: residual mortar content)

Agg	**fraction →**	**4.75-2.36 mm**	**2.36-1.18 mm**	**1.18-0.63 mm**	**0.63-0.30 mm**	**0.30-0.15 mm**	**Total**
AG	Area RM (mm^2)	866.7	147.7	49.0	12.1	8.6	1084.1
	Area OVA (mm^2)	824.5	124.7	33.7	7.7	4.3	994.9
	RMC (%)	**42.0**	**44.9**	**50.1**	**52.1**	**58.0**	**52.1**
SG	Area RM (mm^2)	628.3	75.8	25.6	12.2	5.5	747.4
	Area OVA (mm^2)	1280.3	124.6	40.0	16.4	4.5	1465.8
	RMC (%)	**24.7**	**28.9**	**29.9**	**33.0**	**45.1**	**33.8**

TABLE 2: Composition of each of the size fractions of the *crusher's fines* (AG: Alberta gravel; SG: Springhill greywacke; RM: Residual mortar; OVA: Original virgin aggregate; RMC: residual mortar content)

Agg	fraction →	4.75-2.36 mm	2.36-1.18 mm	1.18-0.63 mm	0.63-0.30 mm	0.30-0.15 mm	Total
AG	Area RM (mm^2)	894.8	121.2	47.5	16.7	10.7	1090.9
	Area OVA (mm^2)	360.8	61.2	28.5	12.5	10.6	473.6
	RMC (%)	**63.1**	**57.7**	**53.5**	**47.9**	**40.9**	**69.7**
SG	Area RM (mm^2)	1144.9	132.7	70.5	17.3	5.9	1371.3
	Area OVA (mm^2)	402.1	53.1	37.3	9.8	3.6	505.9
	RMC (%)	**65.5**	**62.5**	**55.8**	**54.1**	**52.2**	**73.0**

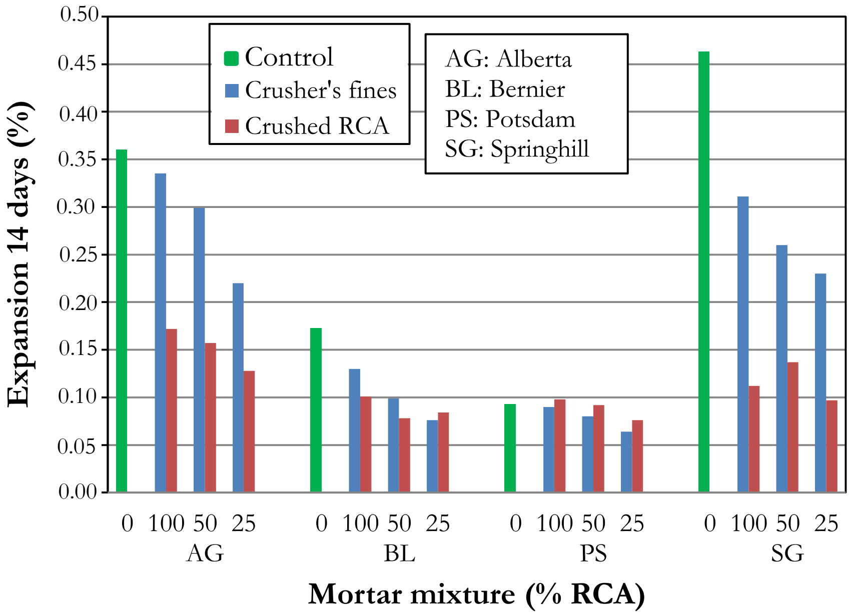

FIGURE 1: 14-day accelerated mortar bar expansions of the *crusher's fines* and the *crushed RCA* incorporating the four OVA selected for this study.

A

B

FIGURE 2: Exposure blocks incorporating the Alberta (A) and the Springhill (B) aggregates that were used for the manufacture of the RCA.

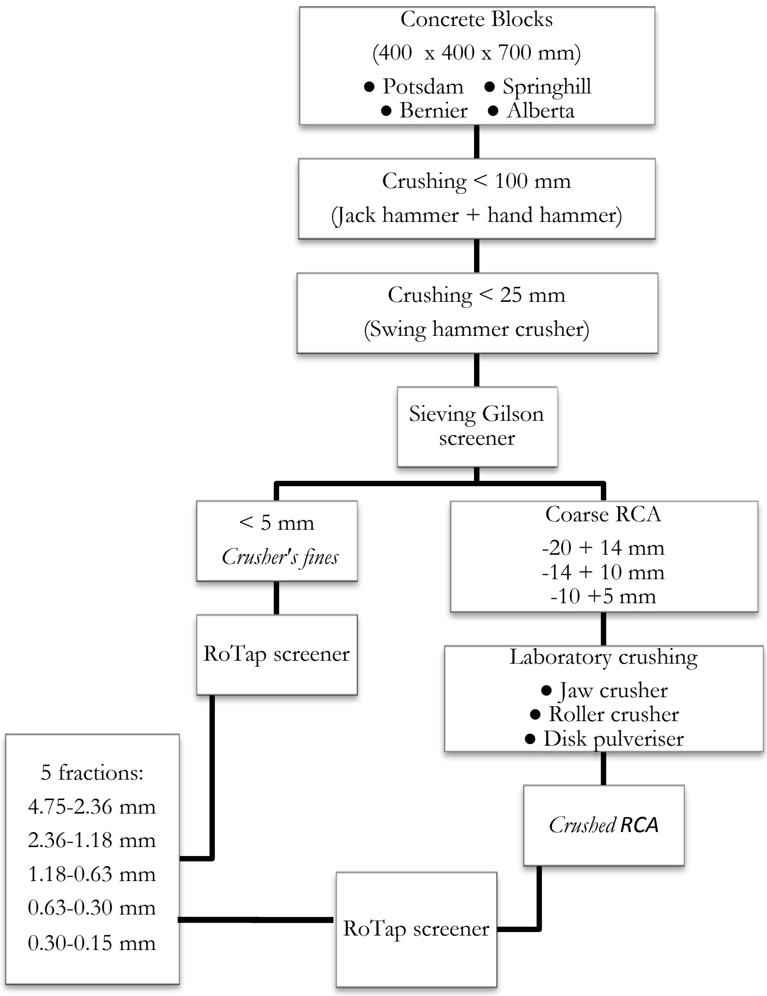

FIGURE 3: Description of the preparation of the RCA

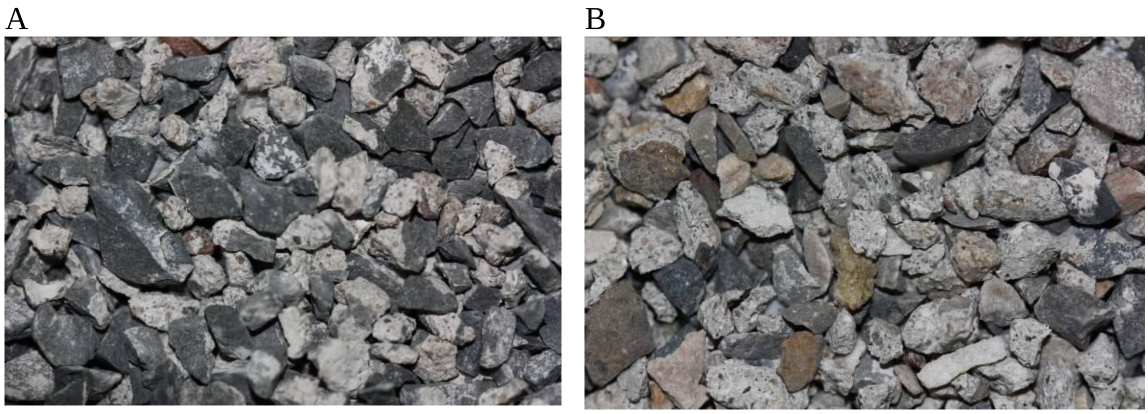

FIGURE 4: RCA incorporating the AG (A) and SG (B) aggregates (14-20 mm size fraction)

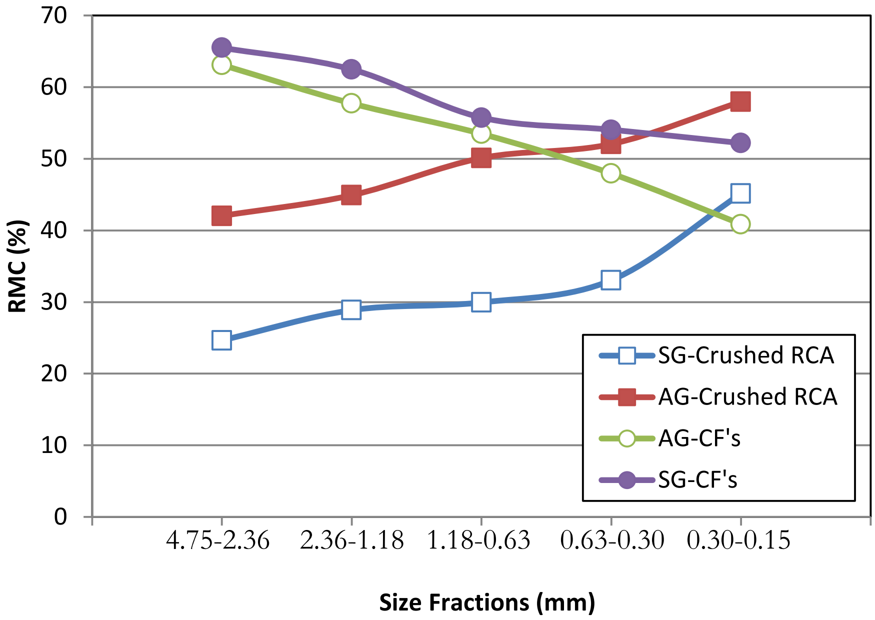

FIGURE 5: Total residual mortar content for the different particle sizes of the crushed RCA and crusher's fines (AG: Alberta gravel; SG; Springhill greywacke).

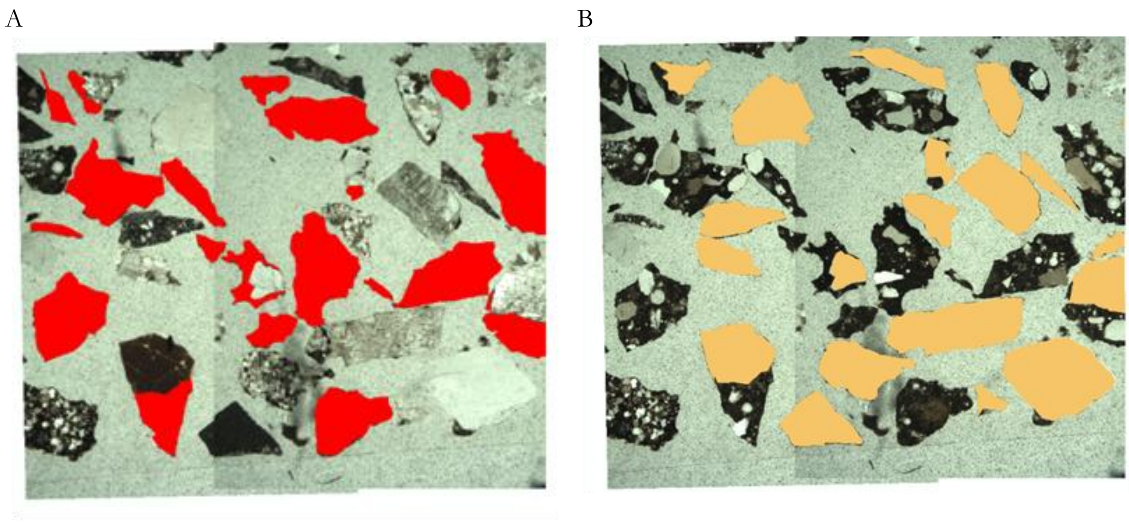

FIGURE 6: Example of segmentation of RCA particles (A) and OVA particles (B) for Alberta gravel (SG) (thin section incorporating aggregate particles of 2.36-1.18 mm in size). Only the particles appearing entirely on the picture are treated.

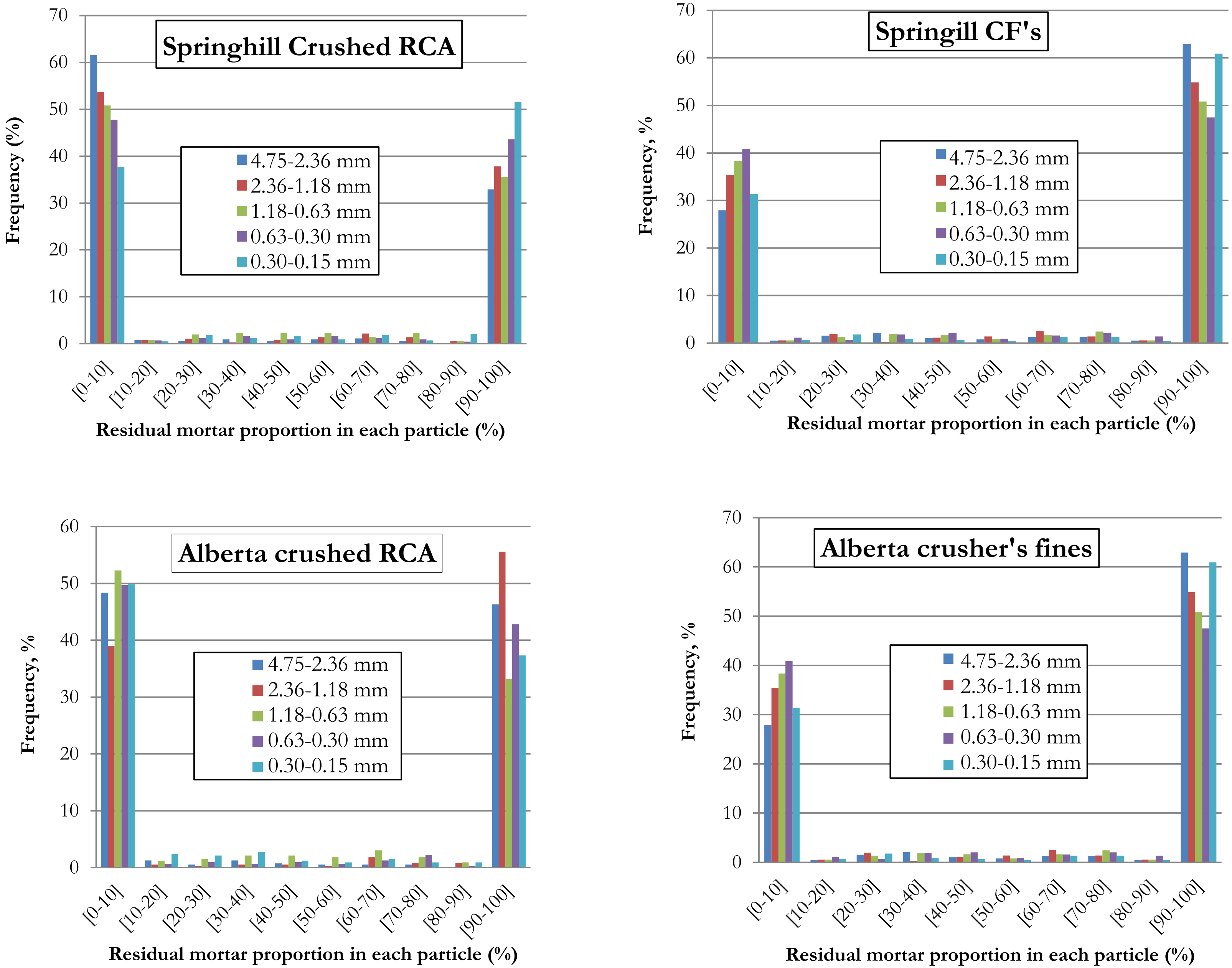

FIGURE 7: Frequency of particles incorporating different proportions of RM (in increments of 10%)

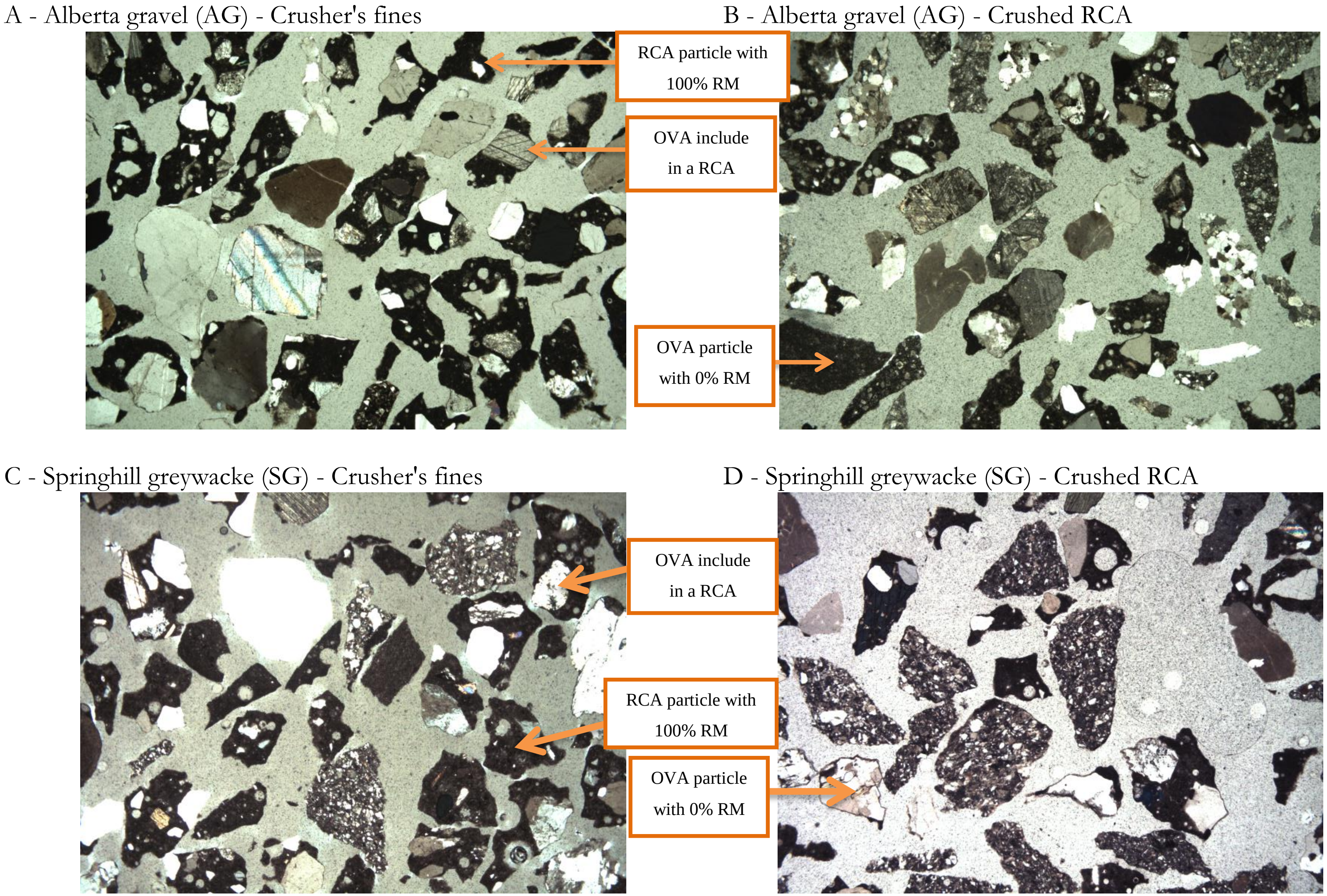

FIGURE 8: Micrographs (thin sections) of fine recycled aggregate particles (size fraction 1.18 - 0.63 mm).