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The influence of crushing method on recycled concrete properties

M.V.A. Florea and H.J.H. Brouwers

Eindhoven University of Technology

Abstract

Recycled concrete aggregates are mainly used for road construction, but another interesting application would be their incorporation into concrete mixes. So far, such an application is hindered by the loss of mechanical properties of recycled aggregates concrete. However, through an efficient crushing technique, recycled concrete can be a beneficial addition. This study deals with properties (particle size distribution, density, thermal treatment reaction, oxide and mineralogical composition) of a large number of recycled concrete fractions, obtained through three crushing methods.

Keywords: recycled concrete, cement paste, density, silica content.

Corresponding author's email: m.v.a.florea@tue.nl

Introduction

Attached mortar is the main concern for using recycled concrete aggregates in new concrete; it accounts for the main difference between RCAs and natural aggregates. The attached paste is the main factor that causes the degradation of the new concrete incorporating recycled concrete aggregates. Recycled concrete aggregates with different particle sizes have significantly different amounts of mortar attached to them [1]. Etxeberria et al. [1] had also reported the quantity of adhered mortar increases with the decrease of size of the recycled aggregates, depending on the crushing methods; the attached amount of mortar can vary from 20%-40% m/m of the aggregates. Hansen [2] reported a value of the percentage of attached mortar of up to 60% for 4-8 mm coarse recycled aggregates and 65% for the 0-0.3 mm filler fraction. Padmini et al. [3] reached a similar conclusion. The recycled particles smaller than 2 mm are not considered usable for new concrete by some researchers because of the large amount of attached cement paste [2, 3]. The attached mortar content of the recycled concrete aggregate is called residual mortar content [5]. Mulder et al. [6] reported a thermal treatment method to obtain aggregates with only 2% of hardened cement paste remaining attached to the sand and gravel grains. Kou et al. [7] observed that fine recycled aggregates possessed certain self-cementing abilities because of the unhydrated cement in the core of the cement grains.

Many researchers reported that the densities of the fine and coarse recycled concrete aggregates are lower than natural aggregates; their results seem to be in unanimous agreement [1-3, 7-12]. This is because of the lower density and higher porosity of cement paste attached to the recycled aggregates. However, studies [7, 9 10] show that it is possible to use recycled concrete sand in the production of new concrete without affecting the concrete fresh and hardened properties significantly.

Initial concrete - recipe and properties

A concrete recipe was designed in order to link the initial constituents of concrete to the composition of the recycled material and validate the results. Better quality can be thus ensured since no contaminating materials are mixed in the recycled materials. The final objective is to be able to describe the composition of recycled concrete particles through simple physical analysis and establish some concepts that make knowing the initial composition less critical.

The particle size distributions (PSDs) of the cement and limestone (Table 1) were determined using a Mastersizer 2000 Particle Analyzer. The PSDs of the three aggregate types (N1, G1 and G2 in Table 1) were determined through dry sieving. All aggregates were used as-received in the test program, in wet conditions as this is the case in practice. However, the water content was determined for each aggregate fraction, by drying at 105±5 °C for 24 hours. These values were taken into account when designing the mixes for the test program. The water/binder ratio of the mix was adjusted to take into account the water content of each aggregate type.

The design of the mix is based on the optimal packing density that can be obtained with the chosen materials. The mix design has been optimized by using the mix design optimization algorithm developed by Hüsken & Brouwers [13]. All granulometric information on the used materials has been included into the algorithm for this purpose. The optimal particle size distribution (PSD) for the binder has been calculated using the modified Andreasen & Andersen equation. A water/cement ratio of 0.5 was used, and the concrete was cast into plastic moulds for crushing, besides cubes of 150 mm x 150 mm for strength determination.

The samples were demolded after one day and cured in water at a temperature of 20 °C. The compressive strengths of the cubes at 28 days amounted to 58 MPa.

Table 1. Designed recipe of the initial concrete mixture

Material	Volume [dm³]	Mass [kg]	Mass [%]
CEM I 42.5N	111.0	340.0	14.5
Limestone Powder	15.0	40.8	1.7
Sand N1	271.0	718.2	30.7
Gravel G1	248.8	659.3	28.2
Gravel G2	154.2	408.5	17.5
Water	170.0	170.0	7.3
Air	30.0	-	-
Total	1000.0	2336.9	100.0

Crushing, fractioning and analyzing the recycled concrete aggregates

The crushing of the concrete samples was performed after 91 days from the day of casting. A jaw crusher was used for this purpose. The material was crushed once and dry sieved in order to obtain its particle size distribution. This material will be termed RC-1 throughout this study. Through sieving the following fractions were obtained: < 150 µm (termed RC-1 0-150), 150- 250 µm (termed RC-1 150-250), 250-300 µm (termed RC-1 250-300), 300-500 µm (termed RC-1 300-500), 500 µm – 1 mm (termed RC-1 500-1), 1-2 mm (termed RC-1 1-2), 2-4 mm (termed RC-1 2-4), 4-6 mm (termed RC-1 4-6), 6-8 mm (termed RC-1 6-8), 8-11.2 mm (termed RC-1 8-11.2), 11.2-16 mm (termed RC-1 11.2-16) and 16-32 mm (termed RC-1 16-32). After sieving, the material was brought back to the crusher 9 consecutive times, for a total of 10 crushing times, in order to obtain an optimal crushing. The obtained material, termed RC-2, was again sieved and divided into the same 12 fractions as the first time.

A third crushing method was used, and the generated particles termed RC-3. The crusher used for this purpose is a jaw crusher specially designed for concrete recycling. It is a patented invention under the world patent number WO 2011/142663 [14]. This is a test model modified based on a commercial jaw crusher Fritsch pulverisette 1 model II. The purpose of the machine is to separate concrete into its constituent sand, gravel and cement paste. While the ordinary crushers are usually used only for the purpose of reducing particle sizes which will crush all the component materials randomly; in the case of concrete, this will include crushing through the aggregates as well as between them. This new type of crusher, termed the Smart Crusher SC 1, is intended to separate concrete into the composite materials without the risk of the components themselves being damaged, by adjusting the crushing force to an intermediate one between the average compressive strengths of the aggregates and the one of the hardened cement paste [14].

The concrete used for crushing was cast in plastic moulds in the shape of a truncated cone ($\Phi 1 = 7.5$ cm, $\Phi 2 = 5.5$ cm, $h = 10$ cm) which fit the inlet opening of both the conventional jaw crusher and the test crusher SC 1 as described above. The concrete samples were first pre-crushed by the crusher only to reduce them to smaller pieces which can better fit the inlet. After that, the samples were crushed by another two passes through the machine. Only particles bigger than 2 mm were re-fed to the crusher. The obtained material was sieved using selected ISO sieves according to ISO 3310. The used sieve sizes were 63 µm, 125 µm, 200 µm, 300 µm, 500 µm, 1 mm, 2 mm, 4 mm, 5.6 mm, 8 mm, 11.2 mm, 16 mm and 22.4 mm, which generated 13 corresponding RC-3 fractions. The sieving process was done as described in the European Standard EN 933-1.

Figure 1 shows the particle size distribution of RC-1 and RC-2 and RC-3. It can be seen that the RC-3 particles are smaller RC-2 and RC-1 ones: the SC generated 33.7% m/m particles smaller than 1 mm, while RC-1 produced only 8.8% m/m smaller than 1mm while RC-2 obtained 21.7% m/m of materials in the same size range, which means SC 1 produced 4 times more particles under 1 mm as RC-1. For particles under 0.5 mm, the SC 1 produced 23% m/m of material, the RC-1 produced 6.7% m/m of the total material and the RC-2 generated 13.2% m/m. SC 1 produced about 3 times as much as RC-1 and about 2 times as much as RC-2 of particles under 0.5 mm.

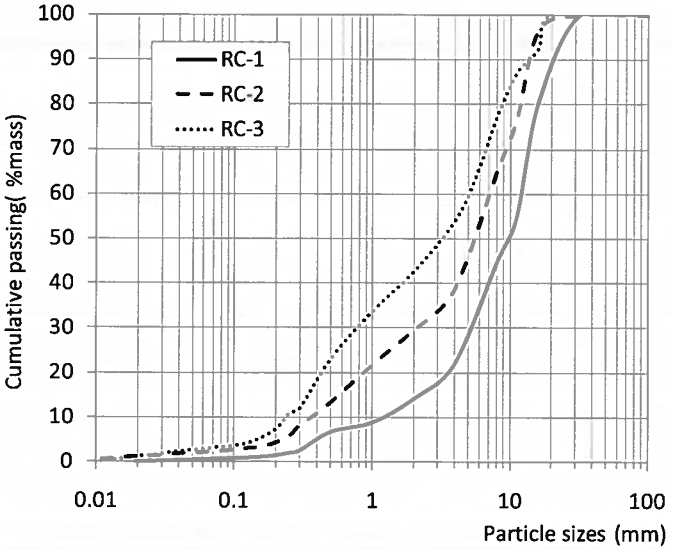

Figure 1. Particle size distributions of the three crushed materials, RC-1 (crushed once) and RC-2 (after 10 crushing times) and RC-3 (from the Smart Crusher SC 1) on a logarithmic scale

Densities of the recycled concrete fractions

Generally speaking, recycled concrete (RC) has a lower density and higher water absorption than the original aggregates used, because of the hardened cement paste that remains attached to the aggregate particles [2]. Higher water absorption causes a higher water/cement ratio if the RC is incorporated in new concrete. It also influences the workability of fresh concrete. Because natural aggregates have higher densities than pure cement paste, recycled aggregates will always have lower densities than the natural aggregates. It can be speculated that for recycled concrete aggregates, the closer their densities to those of natural aggregates are, the less attached mortar they have. Hence, density is an important parameter for determining the quality of RC in practice.

Recycled concrete of different sizes has different cement paste contents which can lead to different densities. In order to avoid the influence of inaccessible pores, all samples were milled into powder by a ball mill at the same speed for 10 minutes. After that, obtained powders from different recycled concrete sizes were put in an oven and dried at 70 °C for 24 hours to avoid the influence of moisture. The densities were measured by a He pycnometer (Micrometrics Accupyc 1340).

Reference densities of controlled cement paste and α-quartz content mixtures, with a milled cement paste content between 0 and 100%, were also measured. The pure cement paste was made from the same cement used for the initial concrete. The water cement ratio used was 0.7. The α-quartz can only be generated by the aggregate, which was shown to be constituted of 98% SiO_2 by XRF measurements. The mixtures of cement paste and sand were blended together and then milled into powders and dried. The density measurement results for the RC-3 series are shown in Table 5. A relationship between the cement paste content and the density of the samples can be observed from the data. For recycled concrete aggregates, the lower the density, the higher the cement paste content. This is further validated by using the TG-DSC analysis.

DSC analysis of recycled concrete fractions

For all fractions of all three materials (RC-1, RC-2 and RC-3), the thermal analysis was performed using a Netzsch STA F1. Both thermogravimetric (TG) and differential scanning calorimetry (DSC) were performed simultaneously on all samples. The thermal analysis was performed in alumina crucibles, up to a maximum temperature of 1100 °C, with heating and cooling speeds of 10 °C/min, and a temperature plateau at 1100 °C for one hour, to ensure steady state.

The DSC curve registers any thermal reaction (exo- or endothermic) which takes place within the sample. These are usually associated with a mass change which can be observed on the TG curve. However, there are reactions which take place without a mass change, but for which thermal effects can be observed. These are usually phase changes (like melting or solidifying of materials) or phase transitions (from one crystallographic form of a compound to another), which take place with the adsorption or release of energy. In the case of the RC samples, such an effect can be observed at approx. 570 °C: the phase transition of α-SiO_2 to β-SiO_2. These effects are quantified using the area under the peak, which is proportional to the concentration of the respective compound within the sample.

These peak areas of the α-quartz were used to determine the quartz content of each recycled concrete aggregates fraction. All the samples prepared for the density test were analyzed by the TG-DSC machine. Eq. 1 ($R^2 = 0.9818$) used to compute the α-quartz contents of all considered samples:

$$100 \cdot x^{DSC}_{\alpha-SiO_2} = -7.2367 \cdot (a^{DSC}_{\alpha\to\beta})^2 + 52.885 \cdot (a^{DSC}_{\alpha\to\beta}) + 2.9026 \qquad \text{(eq.1)}$$

where $x^{DSC}_{\alpha-SiO_2}$ is the mass fraction of α-quartz in the sample and $a^{DSC}_{\alpha\to\beta}$ is the area under the peak corresponding to the α →β-quartz transformation.

Figure 2 (a, b and c) visually shows the breakdown between cement paste and aggregates for all considered fractions. There are some differences to be observed between the three materials. In the case of RC-1 (Figure 2a), a constant increase of α-quartz content with particle size can be noticed. Particles above 8 mm have an α-quartz content over 80%, while the lowest α-quartz content registered is just above 40% (RC-1 0-150 µm). For RC-2 (Figure 2b), a similar increasing trend can be observed. However, the α-quartz content of particles above 1 mm becomes fairly constant at around 80%. The smallest RC-2 fraction (0-150 µm) has an α-quartz

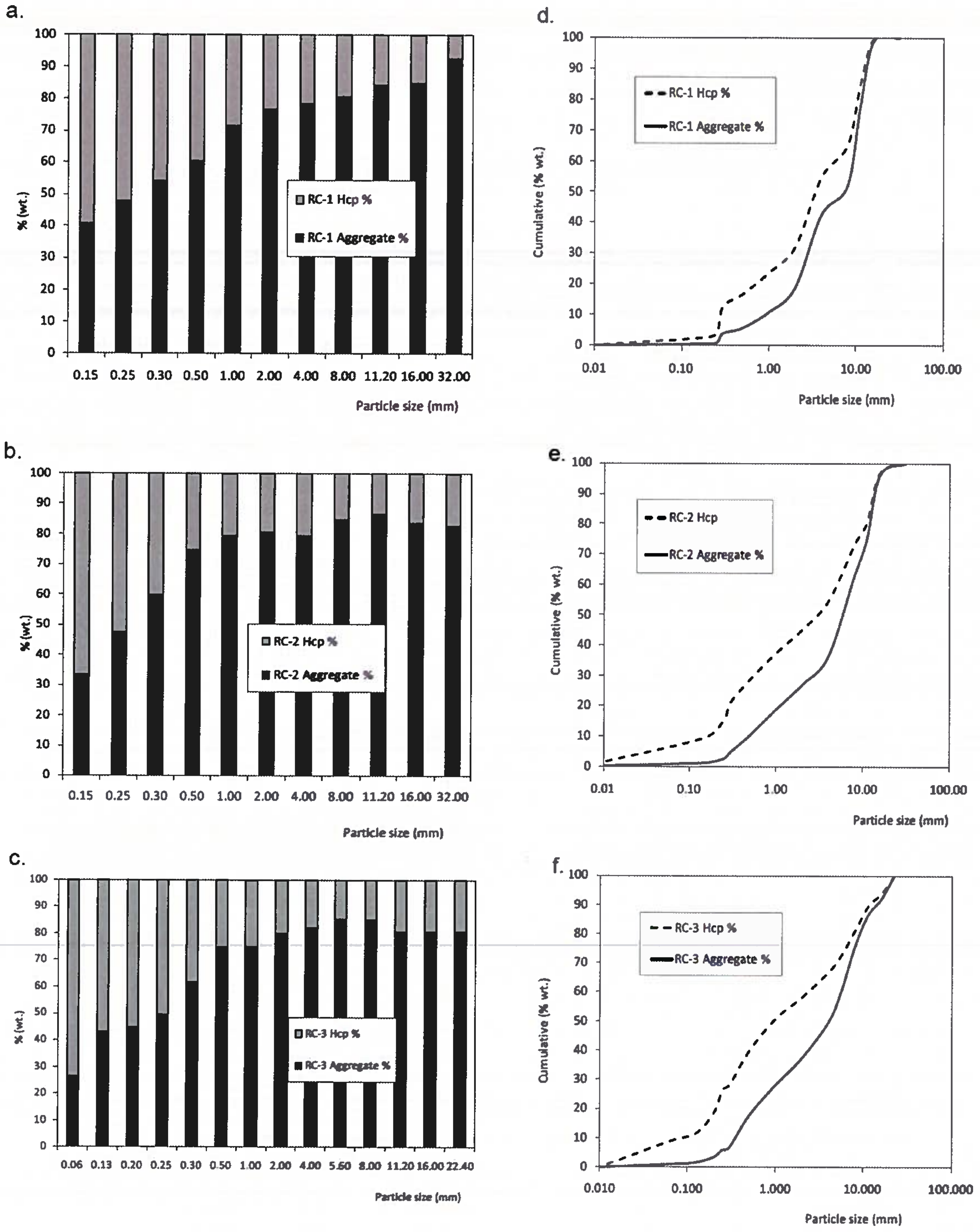

Figure 2. Composition of all recycled concrete fractions divided into the aggregate (α-quartz) and hardened cement paste (Hcp) components: a. RC-1; b. RC-2; c: RC-3 and their respective cumulative distribution of the hardened cement paste and aggregates in d. RC-1; e. RC-2; f: RC-3

content of 33.4%, 20% lower than the corresponding RC-1 fraction. It can be seen from Figure 2c that the RC-3 particles below 63 µm have the lowest α-quartz content of 26.4% among all the analyzed samples. The 63-125 µm fraction contains approximately 42% α-quartz. With the increasing sizes, the α-quartz contents keep increasing until the particles between 5.6-8 mm. The RC-3 fraction with the highest α-quartz content is found to be the one between 5.6-8 mm, which has 85.3% of α-quartz. Figure 2 a-c also illustrate that the bigger recycled aggregates are cleaner than the small recycled aggregates in terms of cement paste content. This explains why the fine recycled concrete particles have higher water absorption values than coarse recycled concrete aggregates. The RC-3 fractions produced by the Smart Crusher SC 1 that are bigger than 2 mm have more than 80% of α-quartz. The lower α-quartz content for particles above 8 mm of RC-3 compared to the 2-8 mm fractions can be explained by the initial composition of the concrete mix. The maximum aggregate dimension used in the mix design was 8 mm, so all crushed concrete particles larger than these will also include a percentage of hardened cement paste in order to account for the larger size.

Figure 2 (d, e and f) represent the cumulative distributions of the two components (aggregate and hardened cement paste), based on the crushing curves of each of the three materials, respectively. For example, for RC-3 (Figure 2f), the values for the mass fractions, together with the content of aggregate and hardened cement paste can be found in Table 2.

Table 2.Mass fraction and hardened cement percentage obtained from DSC and the measured density of all RC-3 fractions, compared to the computed density and hardened cement paste content (eq. 1)

	Mass fraction [%, m/m]	Cement paste fraction [%, m/m] from DSC	Cement paste fraction [%, m/m] from density	Measured density [g/cm^3]	Computed density [g/cm^3]
RC-3 0-63 µm	2.93	73.63	62.18	2.45	2.42
RC-3 63-125 µm	1.12	57.12	53.86	2.48	2.47
RC-3 125-200 µm	3.11	55.32	48.17	2.50	2.48
RC-3 200-250 µm	3.68	50.57	47.79	2.50	2.50
RC-3 250-300 µm	1.05	38.40	46.39	2.51	2.54
RC-3 300-500 µm	11.07	25.20	30.82	2.56	2.58
RC-3 500 µm – 1 mm	10.7	24.89	22.05	2.59	2.58
RC-3 1-2 mm	8.87	20.08	20.32	2.60	2.60
RC-3 2-4 mm	11.38	18.12	17.38	2.61	2.61
RC-3 4-5.6 mm	9.48	14.70	14.08	2.62	2.62
RC-3 5.6-8 mm	13.68	14.88	15.05	2.62	2.62
RC-3 8-11.2 mm	9.97	19.58	16.04	2.62	2.60
RC-3 11.2-16 mm	5.37	19.68	20.47	2.60	2.60
RC-3 16- 32 mm	7.59	19.52	25.65	2.58	2.60

The total of each component computed in this way correlates very well with the initial composition – 22.5% hardened cement paste (hcp) and 77.5 % aggregates for RC-1 and 20.2% hcp and 79.8 % aggregates for RC-2, compared to 22.4 % hcp and 77.6 % aggregates for the initial material. The lower value of hardened cement paste (hcp) for RC-2 is explained by the loss of very fine material during each crushing cycle. The cumulative totals for RC-3 are 76% aggregate and 24% hardened cement paste.

When comparing Figures 2 d-f, a few observations can be made. In terms of the efficiency of recovering the hardened cement paste fraction, crushing just one time using a conventional jaw crusher (RC-1) is more advantageous than crushing the whole material 10 times (RC-2): for RC-1, a 50% recovery of total hcp can be achieved for particles under 2 mm, while the same value corresponds to material under 3 mm for RC-2. Similarly, an 80% cumulative recovery of hcp is observed for material under 10 mm for RC-1 and under 11 mm for RC-2. The 50% cumulative recovery of the aggregates for RC-1 and RC-2 can be observed under 8 mm and 6 mm, respectively. In the case of RC-3, all these parameters will be met at lower particle sizes. The 50% cumulative recovery of hcp is already met for particles under 1 mm, and the 80% recovery for particles under 8 mm, while the 50% cumulative recovery for the aggregates can be achieved for particles smaller than 5 mm.

Another important observation is that the densities of the recycled concrete fractions have a correlation with the α-quartz contents. From the data in Table 2, a linear correlation can be observed between the measured density and α-quartz content obtained from DSC of each fraction, with an R^2 value of 0.9744. Therefore, the density computed using the linear fit, as well as the hardened cement paste content of each fraction estimated using the inverse equation are also shown in Table 2. It has been observed that the estimation of the hardened cement paste content using such a linear correlation is not very accurate (with average relative errors of ~11%, and a maximum relative error of 23%). This was to be expected, since the range of the hcp values is much larger (14-74%) than the one of the densities (2.45-2.62 g/cm^3). However, for the estimation of density from the hcp content, the relative errors are under 1.5% for the whole estimation range, which suggests that this correlation is an appropriate method for the verification of the DSC data.

XRF measurements were performed to check the accuracy of the DSC method. The relative error between the XRF measurement and the computed total SiO_2 content was under a few percent. XRD was also used on all samples to confirm the decreasing trend of α-quartz with particle size.

Conclusions and discussion

In this research, laboratory made concrete was used to mimic the concrete recycling process. Three crushing methods were used to study their influence on the properties of the obtained materials. A conventional jaw crusher was used for the first two crushing methods to obtain the RC-1 and RC-2 materials (one time crushing and 10 times returning through the crusher, respectively) and a specially designed smart crusher prototype [14] was used to obtain the third material (RC-3). The obtained recycled concrete aggregates were collected and separated into different fractions based on the particle sizes. All these fractions were then thermally characterized by their density, thermal treatment reaction and composition. A new method of quantifying the α-quartz content of the samples using the calibrated DSC signal was developed. It was found that the smaller particle size the RCs have, the less α–quartz they contain. It is also found that the density of the RCs has a correlation with the α–quartz content: low density means relatively low α–quartz content. XRF and XRD tests confirmed the decrease of SiO_2 content with particle size.

When comparing the hardened cement paste content of the materials obtained from all three crushing methods, some differences can be observed. The results have shown a much higher cement paste content in the fractions obtained from the Smart Crusher prototype SC 1 (RC-3), as opposed to the conventional jaw crusher. The recovery of the cement paste, in the same particle size range, was improved by 50%, when comparing the RC-3 and RC-1 materials. This information becomes important when it is also correlated with the particle size distribution of the fractions obtained through the two methods. Sieving the two materials (RC-1 and RC-3) showed a much higher output of fines from the SC 1, up to five times in volume for the particles under 1 mm. Therefore, the crushed hardened cement paste particles recovery was 7.5 times the one from the conventional jaw crusher.

Another conclusion was that the fines obtained from the SC 1 contain much less α-SiO_2 than the ones from the RC-1 series. The RC-3 fines contained a maximum of 27% α-SiO_2 in the 0-63 μ fraction and under 42% in the 63-125 μm fraction, as opposed to approx. 40% in the finest fraction obtained from RC-1 and 34.4% for RC-2. An 80% cumulative recovery of the hardened cement paste can be achieved for particles under 10 and 11 mm for RC-1 and RC-2 respectively, while the same recovery rate is reached for RC-3 for particles under 8 mm, which is also an indication that the SC 1-produced aggregates are cleaner than the ones from a conventional jaw crusher.

All in all, it is shown that the crushing method has a large influence on the quality of the produced materials, and that an optimized crushing method can lead to better properties. A difference in both composition and physical properties is observed for various sizes of crushed concrete. The use of recycled concrete sand in mortar mixtures was proven to be beneficial in terms of mechanical properties, showing good promise for the use of such materials in concrete mixes.

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