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Properties of various size fractions of crushed concrete related to process conditions and re-use

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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 aggregate concrete. However, through an efficient crushing technique, which is able to generate relatively clean aggregates, 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. The use of recycled concrete sand, i.e. particle sizes between 150 μm and 2 mm, in new concrete is proven to be promising when the right crushing technique is adopted.

1. Introduction

Recycling of construction and demolition waste (C&DW) is one of the important topics in concrete research nowadays. Oikonomou [1] gives an extensive comparative review of the C&DW recycling all over the world. For the EU, it is estimated that the annual generation of C&D waste is the largest single waste stream, apart from agricultural waste. The recycling goals of most European countries are ambitious—between 50% and 90% of their C&D waste production. In The Netherlands, Germany and Denmark landfilling has become more costly than recycling. In its report on “Recycled concrete”, WBCSD [2] gives a breakdown of C&DW recycling on individual European countries. Among the total C&DW recovery, recycled aggregates account for 6% to 8% of aggregates use in Europe. The greatest users are the United Kingdom, the Netherlands, Belgium, Switzerland and Germany (data from 2005 and 2006 WBCSD [2]). In Japan and some states of the US, the construction industry uses recycled concrete aggregates (RCA) in substituting a proportion of natural aggregates [3,4], while in Europe, most of the recycled C&D debris is downcycled and used for road base or sub-base material (Hansen and Lauritzen [5]).

Generally speaking, once the concrete has been crushed, sieved and maybe decontaminated, the obtained aggregates can be put into use. The produced aggregates are mainly used in four ways: as general bulk fill; as fill in drainage projects; as sub-base or base material in road construction; as aggregate for new concrete [6]. The first three applications are basically a downcycling which uses those recycled aggregates in low grade applications. The fourth one, to apply RCAs in new concrete, seems to be the most favorable one from the sustainability point of view.

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 [7]. Etxeberria et al. [7] 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 [6] 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. [8] 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 [3,6]. The attached mortar content of the recycled concrete aggregate is called residual mortar content [9]. Mulder et al. [10] reported a thermal treatment method to obtain aggregates with only 2% of hardened cement paste remaining attached to the sand and gravel grains. Kou and Poon [11] 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 [6–8,11–16]. This is because of the lower density and higher porosity of cement paste attached to the recycled aggregates. However, studies [11,13,14] show that it is possible to use recycled concrete sand in the production of new

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concrete without affecting the concrete fresh and hardened properties significantly.

Some researchers studied the fresh properties of recycled concrete sand when replacing fine natural aggregates; however, their observations do not seem to be consistent with each other. Kim et al. [17] reported that the workability decreases with the increase of the replacement ratio. Khatib [18] concluded that the different replacement ratios of fine recycled aggregates up to 100% do not influence the workability very much; all the test groups exhibit very good workability without the use of admixtures. Kou and Poon [11] used fine recycled aggregates in the production of high grade self-compacting concrete; the water/cement ratio was determined by the water absorption value of the recycled aggregates. Corinaldesi and Moriconi [13] decreased the water/cement ratio of the recycled aggregate concrete by using superplasticizing admixtures in order to reach the same workability.

For the mechanical properties, different influences of fine recycled aggregates were found by different researchers. Hansen [6] only used coarse recycled aggregates in new concrete, which lead to the same or even higher strength than corresponding control concretes that were made with the same mix proportions but entirely with natural aggregates. Later on, the experiment was repeated but with both fine and coarse recycled aggregates. The result showed an average compressive strength reduction of 30% compared to the control concrete made with natural sand and gravel. Therefore, it was concluded that the use of fine recycled aggregate always has a detrimental effect on the compressive strength of recycled concretes. It was further recommended to screen out and remove all materials below 2 mm in recycled aggregates; it was even suggested to avoid the use of fine recycled aggregate below 4–5 mm altogether. Sim and Park [19] found that the compressive strength of mortar decreased as the amount of the fine RCAs increased; at 100% replacement, a 33% compressive strength loss was found. Khatib [18] used fine recycled aggregates smaller than 5 mm in new concrete production. The results showed a 30% reduction of compressive strength for 100% replacement and a 15% compressive strength reduction for 25% replacement. Shi-Cong and Chi-Sun [16] found that, at a fixed water/cement ratio, the use of fine recycled aggregates decreased the compressive strength and increased the drying shrinkage of the concrete. Kim et al. [17] found the use of fine recycled aggregates in new concrete generally decreased the compressive strength with an increasing replacement ratio, though for 25% replacement, the compressive strength was even higher than the control group; the flexural strength decreased with an increasing replacement ratio but remained acceptable for 25% and 50% replacement ratios. Evangelista and de Brito [14] used fine recycled aggregate to replace sand from 0.074 mm to 1.19 mm; their results showed there was no influence up to 30% fine aggregate replacement. However, the tensile splitting and elasticity were reduced with the increase of the replacement ratio but acceptable for up to 30% replacement.

All the above studies were conducted in laboratories with controlled concrete mixtures, crushing and sieving to obtain recycled concrete aggregates. It is expected that recycled concrete aggregates obtained from field structures have contaminating particles from debris that might reduce their performances in new concretes. All the above studies show that it is possible to use a certain amount of fine recycled aggregates to replace fine natural aggregates in new concrete production. The qualities of fine recycled aggregates have to be strictly controlled and tested in laboratories before their use in new concrete production.

2. Initial concrete

2.1. Recipe

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 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 [20]. 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. The recipe is shown in Table 1. A water/cement ratio of 0.5 was used, and the concrete was cast into plastic molds for crushing, besides cubes of 150 mm × 150 mm for strength determination.

2.2. Particle size distribution of the concrete constituents

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, Table 1) were determined through dry sieving. The cumulative distributions of all the materials, the designed target line and the grading of the combined final mix [20] are shown in Fig. 1.

2.3. Water content of aggregates

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 h. These values were taken into account when designing the mixes for the test program. The water/binder ratio $\left(x_{w_0/b_0}\right)$ of the mix was adjusted to take into account the water content of each aggregate type. Table 2 summarizes the water content of each of the considered aggregates.

2.4. Concrete strength

After mixing, part of the concrete mixture was cast into cubes (150 × 150 × 150 mm, according to EN 12390-3; 2009) for determining the compressive strength. The samples were demolded after one day and cured in water at a temperature of 20 °C. The compressive strengths of the cubes were tested at the ages of 1, 3, 7, 28 and 91 days. Average compressive strengths of three cubes were obtained at each testing age and are shown in Fig. 2 together with their standard deviation, which is very low in all cases.

3. 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

Table 1
Designed recipe of the initial concrete mixture.

Material	Volume [dm^3]	Mass [kg]	Mass [%]
CEM I 42.5 N	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

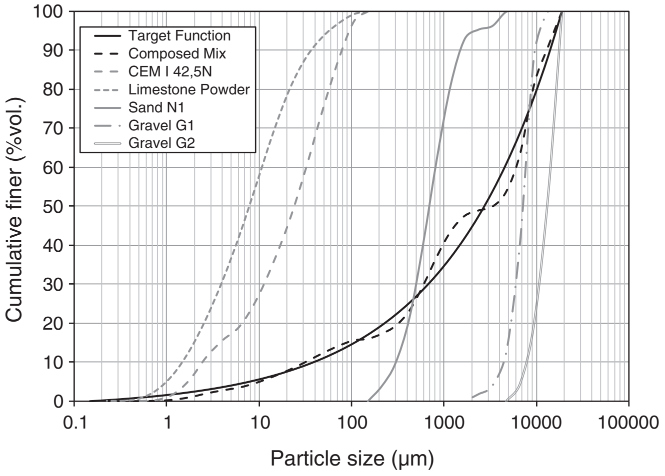

Fig. 1. Particle size distributions of all the used materials (CEM I 42.5 N, limestone powder, sand N1 and two gravel sizes, G1 and G2), the target function and the final mix of the designed initial concrete.

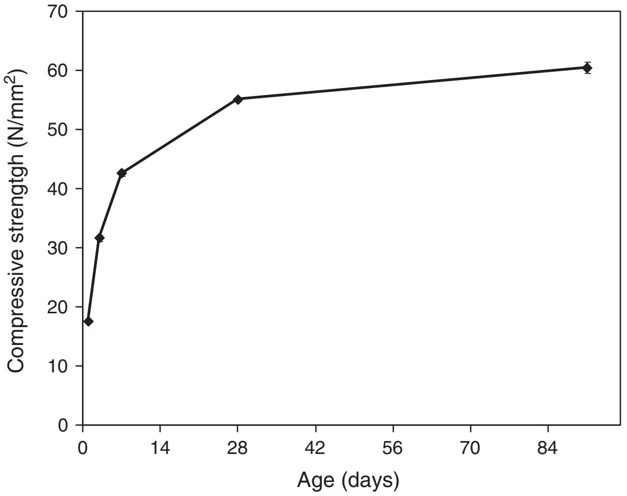

Fig. 2. Compressive strength evolution in time of the initial concrete designed mix (Table 1).

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. While this technique is not feasible from the energy consumption point of view, this material was obtained for comparison purposes with the other crushing techniques.

A third crushing method was used, and the generated particles termed RC-3 [21]. The crusher used for this purpose is a jaw crusher specially designed for concrete recycling. It is a patented invention under a world patent number [22]. 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 on 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 [22].

The concrete used for crushing was cast in plastic molds in the shape of a truncated cone (Φ1 = 7.5 cm, Φ2 = 5.5 cm, h = 10 cm) which fit the inlet opening of the test crusher SC 1 as described in Section 2. 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 concretes 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 by using selected ISO sieves according to ISO 3310. The used sieve sizes are: 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.

Table 2
Water content of aggregates used for the initial concrete mix and their minimum and the maximum particle sizes.

Material	Water content (% of initial dry mass)	D_{min} (μm)	D_{max} (μm)
Sand N1	0.05	0.128	125
Gravel G1	0.10	0.275	5600
Gravel G2	0.10	710	8000

Table 3 shows the difference between the cumulative passings of the three obtained materials. The finest fractions (under 500 μm) were analyzed using a Malvern Mastersizer 2000. The characteristic dimensions of $d_{0.1}$, $d_{0.5}$ and $d_{0.9}$ (corresponding to the mesh size for the passing of 10%, 50% and respectively 90% of the material), as well as the D_{min} and D_{max} of the finer fractions of all three materials are presented in Table 3. The analysis confirmed the smaller particle size of RC-2. Also, a larger scatter of the particle sizes could be seen, as $d_{0.9}$ is in almost all cases higher than the sieve size used for obtaining the fraction. Moreover, both D_{min} and D_{max} show a wider PSD than indicated by the sieving step. It can be seen that the D_{min} and D_{max} values of RC-1 and RC-2 fractions sieved between the same sizes are comparable. RC-2 has the same D_{min} as the corresponding RC-1 fractions or D_{min} is higher (in the case of RC-2 250–300). Conversely, D_{max} is consistently the same or lower in the case of RC-2, when compared to the corresponding RC-1 fraction. RC-3 fractions consistently have a much lower D_{min}, but higher D_{max} values, which suggests that the particles have an acicular shape in order to pass through the sieve openings. This suggests that the RC-2 fractions

Table 3
Characteristic particle size distribution parameters—D_{min}, D_{max}, $d_{0.1}$, $d_{0.5}$ and $d_{0.9}$ measured for the finest fractions of RC-1, RC-2 and RC-3.

	D_{min} [μm]	D_{max} [μm]	$d_{0.1}$ [μm]	$d_{0.5}$ [μm]	$d_{0.9}$ [μm]
RC-1 0–150 μm	0.955	208.930	10.9	68.5	169.2
RC-1 150–250 μm	91.201	478.630	134.8	212.8	334.1
RC-1 250–300 μm	138.038	630.957	212.7	310.5	450.3
RC-1 300–500 μm	208.930	831.764	287.1	459.2	720.4
RC-2 0–150 μm	0.955	208.930	6.0	49.7	127.4
RC-2 150–250 μm	91.201	416.869	132.7	204.8	300.0
RC-2 250–300 μm	158.458	549.541	217.8	306.5	417.9
RC-2 300–500 μm	208.930	724.436	278.9	414.9	597.1
RC-3 0–150 μm	0.478	275.423	4.36	45.7	158.5
RC-3 250–300 μm	0.724	724.436	19.95	363.1	514.1
RC-3 300–500 μm	0.954	954.9	316.22	478.6	696.4

have a narrower range and are composed of finer particles, which is also seen from the $d_{0.1}$, $d_{0.5}$ and $d_{0.9}$ values, while the RC-3 fractions have characteristic values intermediate between the RC-1 and RC-2 materials, excepting the finest range.

Fig. 3 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 1 mm 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 that of 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 the particles under 0.5 mm.

Fig. 4 shows all the cumulative PSDs of the finer fractions (0–150 and 250–300 μm) of both materials. While the RC-3 fractions are the finest of all three crushing methods, the RC-2 material is finer than the RC-1 for the smaller fraction but it has larger particles in the 250–300 μm range. This can be explained on one side by the increased percentage of fines under this dimension of RC-2 when compared to RC-1 and on the other side by the loss of fines during the consecutive crushing steps.

4. Densities of the recycled concrete aggregates

Generally speaking, recycled concrete aggregates (RCA) have 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 [6]. Higher water absorption causes a higher water/cement ratio if the RCA 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 RCA in practice.

Recycled concrete aggregates of different sizes have different cement paste contents which can lead to different densities. In order to avoid the influence of inaccessible pores, all the samples were milled into powder by a ball mill at the same speed for 10 min. After that, obtained powders from different recycled concrete sizes were put in an oven and dried at 70 °C for 24 h to avoid the influence of moisture. The densities were measured by a He pycnometer (Micrometrics Accupyc 1340); the results for the RC-3 series are presented in Fig. 5 [21].

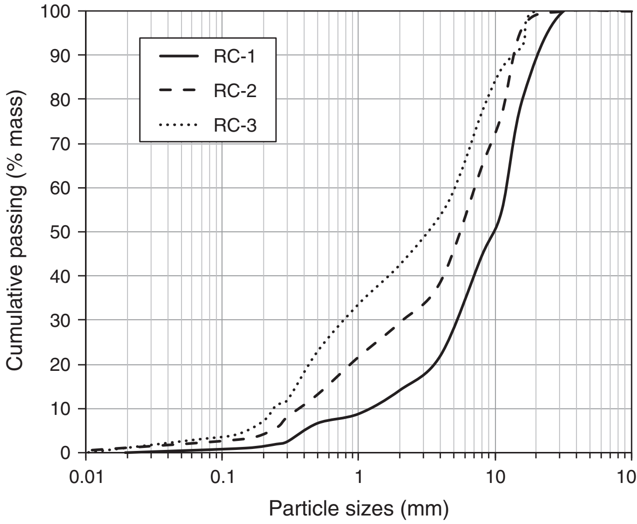

Fig. 3. Particle size distributions of the three crushed materials, RC-1 (crushed once) and RC-2 (after 10 crushing times) and RC-3 (from the Smart Crusher SC 1) on a logarithmic scale.

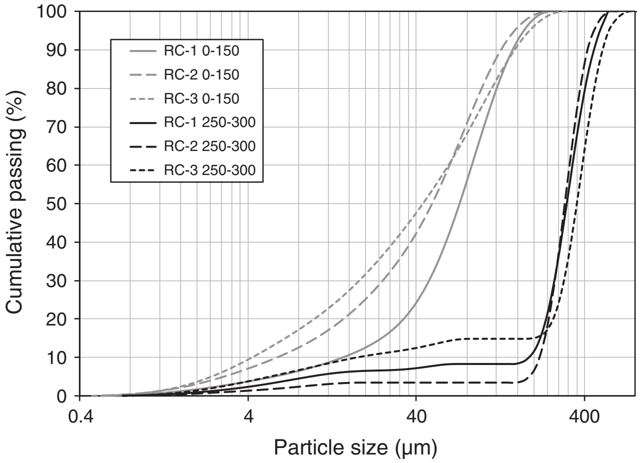

Fig. 4. Particle size distributions of RC-1, RC-2 and RC-3, fractions 0–150 and 250–300 μm.

As can be seen from Fig. 5, particles smaller than 63 μm have the density of 2.45 g/cm^3 which is the lowest density among all the recycled materials. The densities have an increasing trend with particle size until particles between 4 mm and 5.6 mm; the densities then stabilize at around 2.62 g/cm^3 and decrease when the particles are bigger than 8 mm. As stated before, the D_{max} of the gravel used for the initial concrete was 8 mm. Recycled aggregates above 8 mm are considered to have a large amount of cement paste attached to the surface. The density decrease found for particles bigger than 8 mm can thus be explained.

Reference densities of controlled cement paste and α-quartz content mixtures 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 pure cement sample was cast in molds with the dimensions of 40 mm × 40 mm × 160 mm and cured under standard conditions for 8 months. Then, the hardened paste was crushed into small pieces. 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 with the ratios shown in Table 4, 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.

5. DSC analysis of recycled concrete aggregates

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 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. As an example, Fig. 6 shows the TG-DSC analysis results of RC-1 300–500 μm.

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

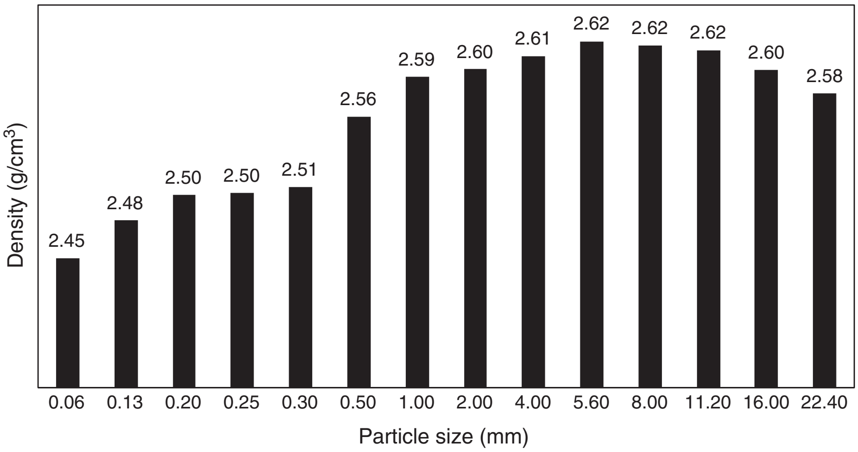

Fig. 5. Densities of all RC-3 fractions obtained by the Smart Crusher SC1.

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 Fig. 6, 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 (Section 4, Table 4) were analyzed by the TG-DSC machine. A calibration curve was also obtained by analyzing mixtures from Table 4 with known α-quartz contents. Fig. 7 shows the calibration curve and the corresponding fitted line used to compute the α-quartz contents of all considered samples

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

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 $\alpha \to \beta$-quartz transformation.

Figs. 8(a, b and c) visually show 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 (Fig. 8a), 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 (Fig. 8b), 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 content of 33.4%, 20% lower than the corresponding RC-1 fraction. It can be seen from Fig. 8c that the RC-3 particles below 63 μm have the lowest α-quartz content of 26.4% among all the analyzed samples. The remaining 73.6% of the sample is composed of hardened cement paste. 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 and 8 mm. The RC-3 fraction with the highest α-quartz content is found to be the particles between 5.6–8 mm, which has 85.3% of α-quartz. Figs. 8a–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 aggregates 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.

Table 4
Mixtures of pure hardened cement paste and Norm sand, used for DSC and density estimations.

Hardened cement paste (%mass)	Milled sand (%mass)	Density (g/cm^3)
0	100	2.65
20	80	2.59
40	60	2.55
60	40	2.49
80	20	2.39
100	0	2.30

Figs. 9(a, b and c) 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 (Fig. 9c), the values for the mass fractions, together with the content of aggregate and hardened cement paste can be found in Table 5. 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 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 Figs. 9a–c, 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.

Table 5
Mass fraction, breakdown into aggregate and hardened cement fractions 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]	Aggregates 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	26.37	73.63	62.18	2.45	2.42
RC-3 63–125 μm	1.12	42.88	57.12	53.86	2.48	2.47
RC-3 125–200 μm	3.11	44.68	55.32	48.17	2.50	2.48
RC-3 200–250 μm	3.68	49.43	50.57	47.79	2.50	2.50
RC-3 250–300 μm	1.05	61.60	38.40	46.39	2.51	2.54
RC-3 300–500 μm	11.07	74.80	25.20	30.82	2.56	2.58
RC-3 500 μm–1 mm	10.7	75.11	24.89	22.05	2.59	2.58
RC-3 1–2 mm	8.87	79.92	20.08	20.32	2.60	2.60
RC-3 2–4 mm	11.38	81.88	18.12	17.38	2.61	2.61
RC-3 4–5.6 mm	9.48	85.30	14.70	14.08	2.62	2.62
RC-3 5.6–8 mm	13.68	85.12	14.88	15.05	2.62	2.62
RC-3 8–11.2 mm	9.97	80.42	19.58	16.04	2.62	2.60
RC-3 11.2–16 mm	5.37	80.32	19.68	20.47	2.60	2.60
RC-3 16–32 mm	7.59	80.48	19.52	25.65	2.58	2.60

Fig. 10a shows the density of the samples (right y-axis) on the same graph with the α-SiO_2 contents (left y-axis). A good agreement between the density and α-quartz content of the recycled concrete aggregates can be observed. This suggests that density measurements can be used for the recycled concrete aggregates α-quartz content estimation.

From the data in Table 5, 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 (Fig. 10b). 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 5. 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.

6. XRF validations

The accuracy of the method described in Section 5 is validated by X-ray fluorescence analysis of the same samples. Part of the XRF result is shown in Table 6. The mass fraction of SiO_2 measured by XRF $\left(x^{XRF}_{SiO_2}\right)$ in the recycled concrete fractions is the sum of α-quartz and SiO_2 from the hydration products. The mass fraction of SiO_2 from the hydration products can be traced back from the chemical composition of the hardened cement paste fraction $\left(x^{hcp}_{SiO_2}\right)$, which in turn is formed by cement and water $\left(x_{cem+x_{w_0/b_0}}\right)$, correcting for the 1.7% of limestone which is also present in the mix. The cement used for the initial concrete recipe, ENCI CEM I 42.5 N, has a SiO_2 content of 0.2 m/m. The mass fraction of α-quartz in each considered recycled concrete fraction is measured by the DSC $\left(x^{DSC}_{\alpha-SiO_2}\right)$ method. The relationship can be expressed as:

$$x^{total}_{SiO_2} = x^{DSC}_{\alpha-SiO_2} + \left(1-x^{DSC}_{\alpha-SiO_2}\right)\cdot x^{hcp}_{SiO_2} \tag{2}$$

where

$$x^{DSC}_{\alpha-SiO_2} + x_{hcp} = x^{DSC}_{\alpha-SiO_2} + \left(x_{cem+w_0/b_0}\right) = 1 \tag{3}$$

$$x^{hcp}_{SiO_2} = 0.2\cdot x_{cem}\cdot\frac{1}{1+w_0/b_0}. \tag{4}$$

To take RC-3 particles between 200 and 250 μm as an example, the SiO_2 content measured by XRF is 57.38%. The α-quartz content determined by TG-DSC is 49.43%, which means the hydration products have the percentage by weight of 50.57%. As is known that ENCI CEM I 42.5 N has the SiO_2 content of 0.2 m/m, and the used water/binder ratio w_0/b_0 was 0.5, the SiO_2 fraction from hydration products

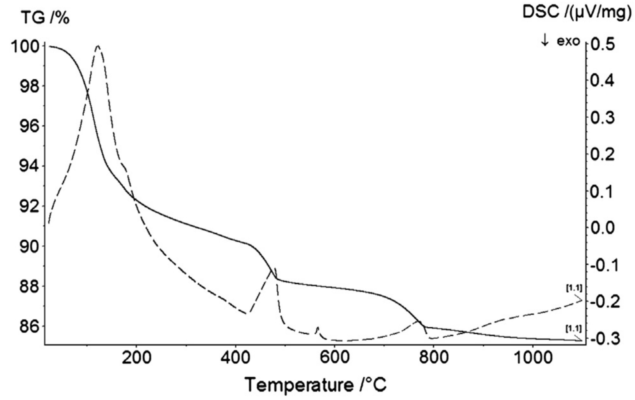

Fig. 6. TG and DSC (dotted line) curves of RC-1 300–500 μm.

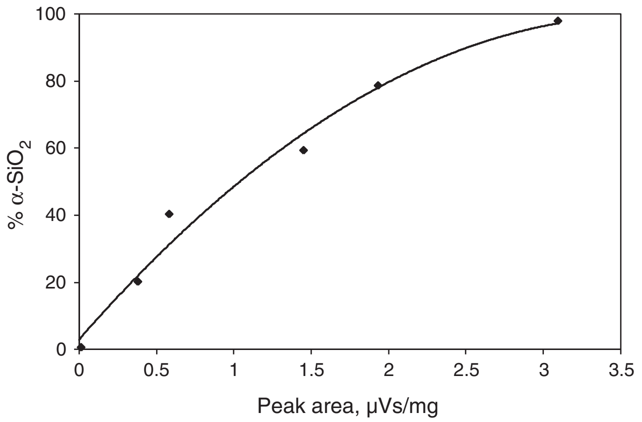

Fig. 7. Calibration curve of α-quartz content against DCS measurements for sand-hardened cement paste mixtures (compositions in Table 4).

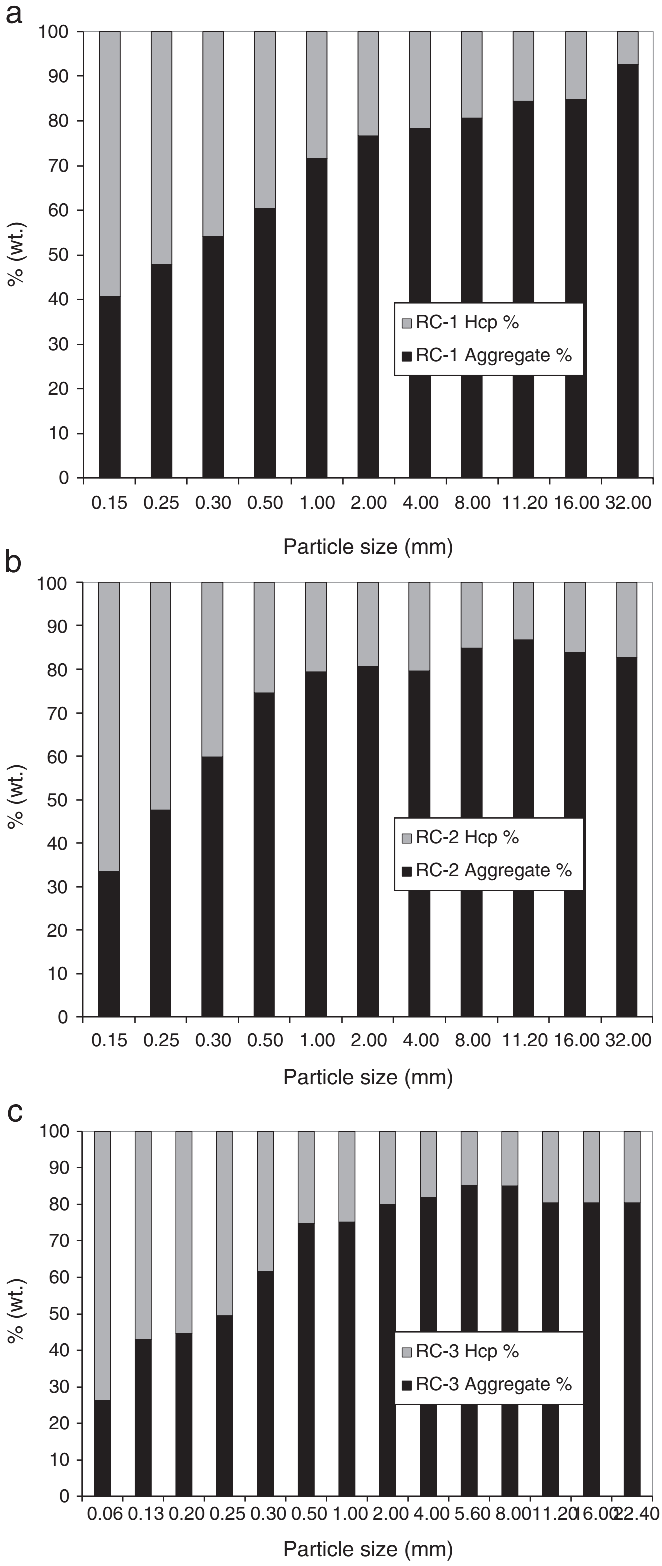

Fig. 8. Composition of all recycled concrete fractions divided into the aggregate (α-quartz) and hardened cement paste (Hcp) components: a. RC-1; b. RC-2; c: RC-3.

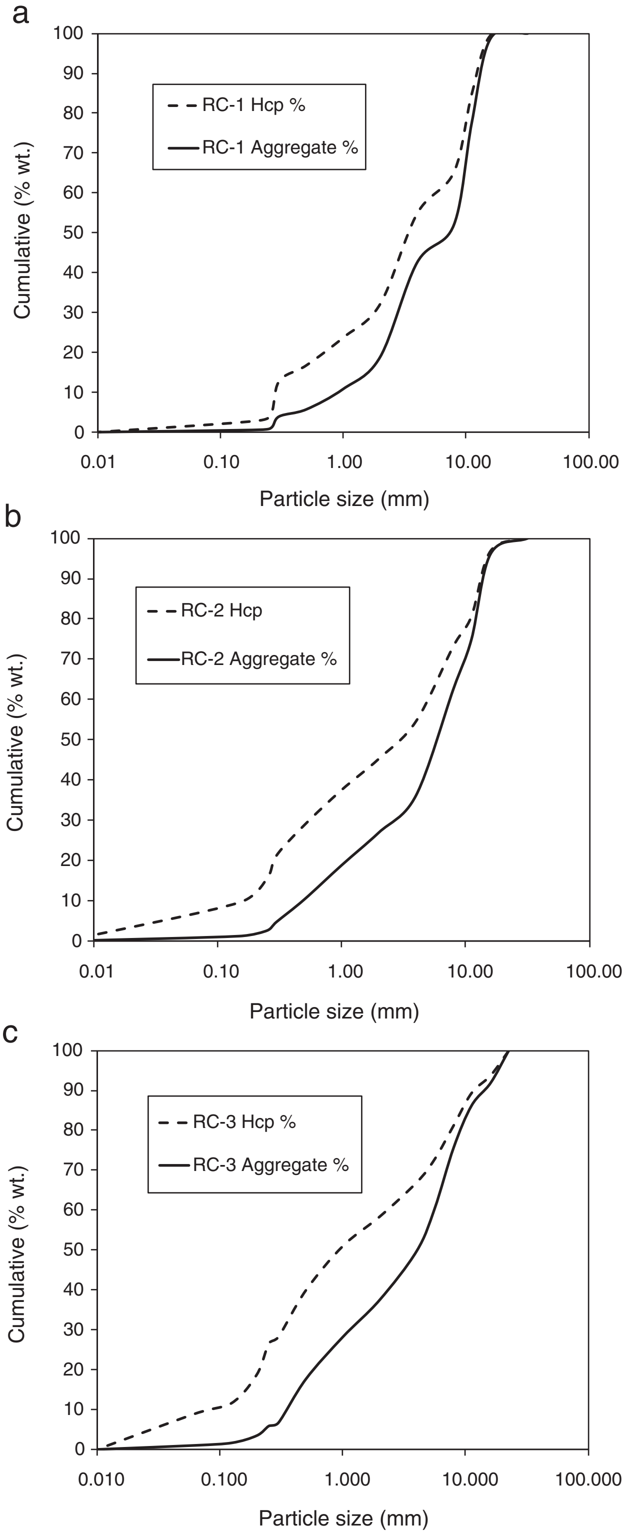

Fig. 9. Cumulative distribution of the hardened cement paste and aggregates in a. RC-1; b. RC-2; c: RC-3.

becomes 6.23%. Therefore, the total SiO_2 content determined by TG-DSC method is 55.67%, the error between the XRF result and the TG-DSC method being under 3%.

Table 6 shows this computation for all fractions of RC-3 under 250 μm. There is an additional expected error of the XRF measurement (besides the sample preparation errors which were minimized in terms of finely grinding and homogenizing), due to the computation of all elements in oxide form, since the TG analysis also shows the presence of carbonation to a larger extent than the one provided by the limestone. Therefore, the fit between the two analytical measurement techniques is considered to be a good indication of the accuracy of the results.

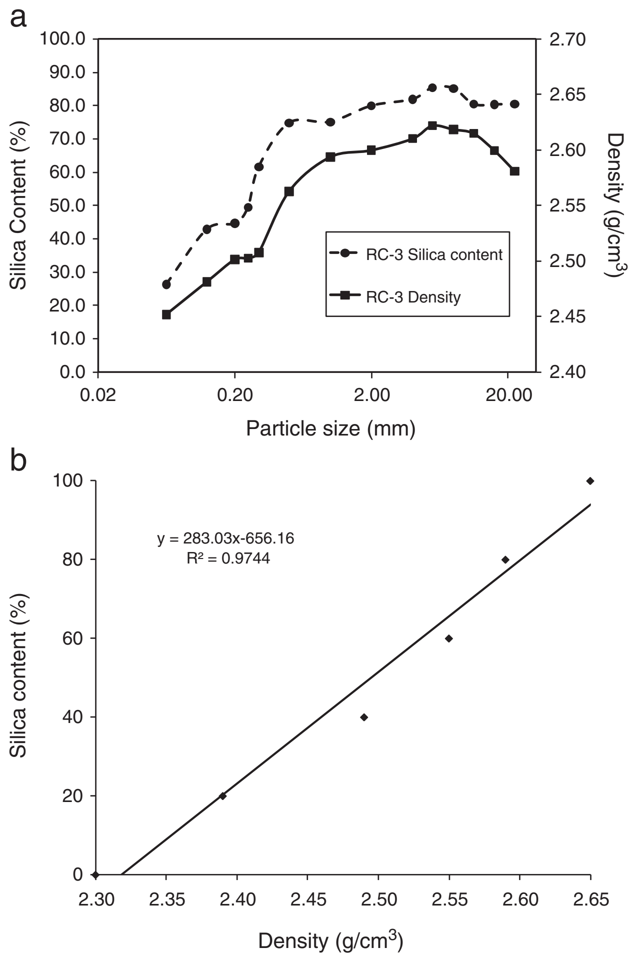

Fig. 10. a. Density (g/cm^3) and α-quartz content (%) of all fractions of RC-3, presented on a logarithmic scale; b. Relationship between the density and silica content of RC-3.

7. XRD and SEM/EDX

X-ray diffraction analysis was performed on all samples considered. Given their similarity, only a few selected fractions will be presented. Peaks belonging to SiO_2, $Ca(OH)_2$ and ettringite were identified in order to show the presence of hydrated cement paste and aggregates. Additional tests were performed on the initial natural aggregates, which were confirmed by XRF to have between 92 and 98% quartz content. For the ease of calculation, all aggregates were considered to be 96% α-quartz. Fig. 11 shows the RC-2 fractions with their complete diffraction patterns. It can be observed that the aggregate content increases with increasing particle size, while the hcp content is higher for the smaller fractions, as it has also been observed using the DSC.

Table 6
XRF-obtained SiO_2 content of the four finest RC-3 fractions, compared to the DSC results and the computed total silica (Eq. (3)).

	$x^{DSC}_{\alpha-SiO_2}\cdot 100$ (%)	$x^{total}_{SiO_2}\cdot 100$ (%)	$x^{XRF}_{SiO_2}\cdot 100$ (%)
RC-3 0–63 μm	26.37	35.45	39.91
RC-3 63–125 μm	42.89	50.52	52.10
RC-3 125–200 μm	44.68	51.50	55.34
RC-3 200–250 μm	49.43	55.67	57.38

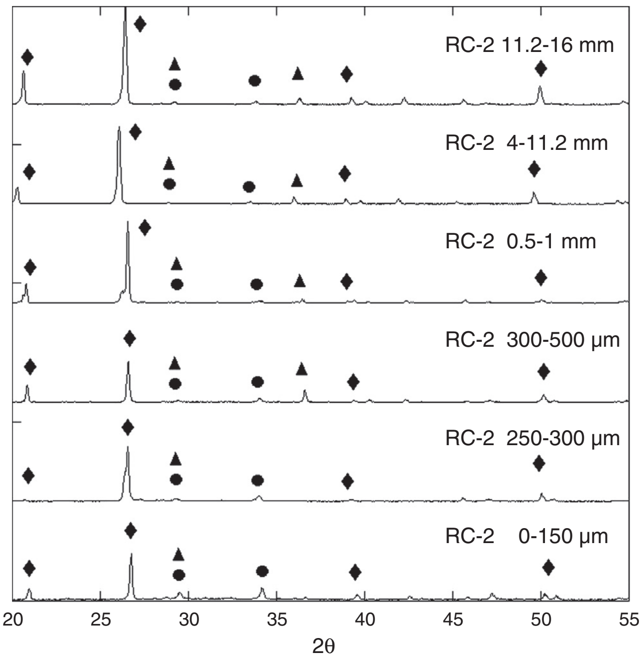

Fig. 11. XRD analysis of RC-2 fractions, with relative peak intensities; ♦ = α-quartz, ● = portlandite, ▲ = ettringite.

The microstructure of the hydrated cement paste and the morphological characteristics of fine recycled concrete aggregates (RC-3 0–63 μm) were investigated by scanning electron microscopy (SEM), with magnifications between 500× (a. in Fig. 12) up to 5000× (b. in Fig. 12). The energy dispersive X-ray (EDX) detector was employed simultaneously for the elemental analysis of the recycled concrete fractions.

It can be seen from Fig. 12 (c., 4000×) that a sand grain with cement hydration products attached to its surface. The EDX map (Fig. 12d) of silicon was taken for the exact same sample image, which verified that the "support" grain is indeed SiO_2. The elemental map of Ca for instance shows an even distribution, which confirms the spread of the hydration products on the surface of the SiO_2 grain. These observations confirm the supposition that fine recycled concrete grains have irregular shapes, and that acicular particles can be observed, which explain the increased D_{max} of each fraction (Table 3 and Section 3). Also, the fact that hydration products are sometimes stuck on a crushed aggregate grain explains the residual content of α-quartz even in fine recycled concrete fractions.

8. Recycled concrete sand replacement test

Recycled concrete sand (RCS) obtained from the SC 1 crusher with particle sizes up to 2 mm was used to replace Norm sand, as specified in EN 196-1. RCS, designed to have the same particle size distribution as Norm sand, was used to replace 100% Norm sand (NS). The PSD of the sieved Norm sand and corresponding RCS are presented in Table 7 [21]. The mix proportioning of the tested mortars was done according to EN 196-1, using CEM I 42.5 N and replacing 100% of the specified norm sand with RCS particles.

8.1. Fresh mortar consistence

Due to the attached cement paste on the RCS surface, mortar samples made from RCS need much more water in order to obtain a desirable consistence. 1% m/m of superplasticizer (SP) was added to the mortar mixture. The RCS mortar sample without SP was too dry to flow; it collapsed instead of spreading out during the mini-slump test using a Hägermann cone. With 1% m/m of SP, the mortar sample

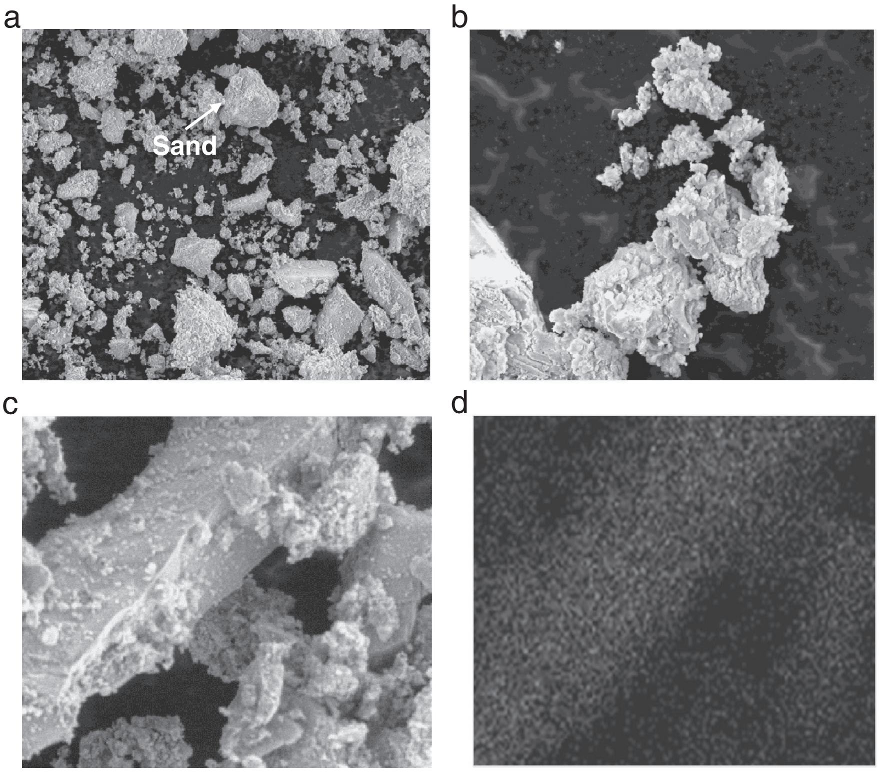

Fig. 12. SEM image of a RC-3 0–150 μm particles (a. 500× and b. 5000×) showing the hydration products of cement and a silica fragment covered with hydration products (c. 4000×) and its silicon map from EDX (d.).

had a spread value of 123 mm, still lower than the reference mortar of 139 mm, but flowability was achieved.

8.2. Strength

The obtained 3 days, 7 days and 28 days flexural and compressive strengths of the reference NS and the RCS mortars are presented in Figs. 13 and 14. It can be seen that replacing 100% of Norm sand by recycled concrete sand increases the mortar sample strength. For the flexural strength, the 3 days strength increased by 45.3%, the 7 days strength increased by 33.2% and the 28 days strength increased by 13.7%. As for the compressive strength, the 3 days strength increased by 65.6%, the 7 day strength increased by 40.3% and the 28 day strength increased by 1.1%. Based on the flexural and compressive strength values, it can be stated that using the RCS to replace 100% of the Norm sand (NS) by using 1% m/m of superplasticizer can increase the mortar strength. Another conclusion is that by using RCS together with superplasticizer to replace NS in standard mortar can lead to the same initial strength but using less cement.

The RCS mortar has much higher early strength than the Norm sand mortar, especially for the 3 day strength and 7 day strength. The 3 days flexural strength of the RCS mortar reaches 69.6% of its 28 days value; the 3 days compressive strength of the RCS mortar (100% RCS) reaches 69.1% of its 28 day strength, while for the Norm sand mortar sample (100%NS), the values are 54.5% and 42.1% respectively. It can be concluded that by using the RCS to replace 100% of Norm sand along with 1% m/m of superplasticizer can speed up the mortar strength development. An explanation for the increased flexural strength can be the broken shape of some of the particles of RCS, which can interlock, as opposed to rounded Norm sand particles. The higher early strengths can be due to the fact that the RCS fines

Table 7
Particle size distributions of Norm sand (according to En 196-1) and the corresponding designed mix of RC-3 sand (RCS).

Particle size (mm)	Norm sand (g)	RCS (g)
<0.075	2.9	3.0
0.075–0.15	120.8	121.0
0.15–0.50	316.2	318.0
0.50–1.0	428.3	430.0
1.0–1.4	250.9	251.0
1.4–2.0	225.9	227.0
Total (g)	1345.0	1350.0

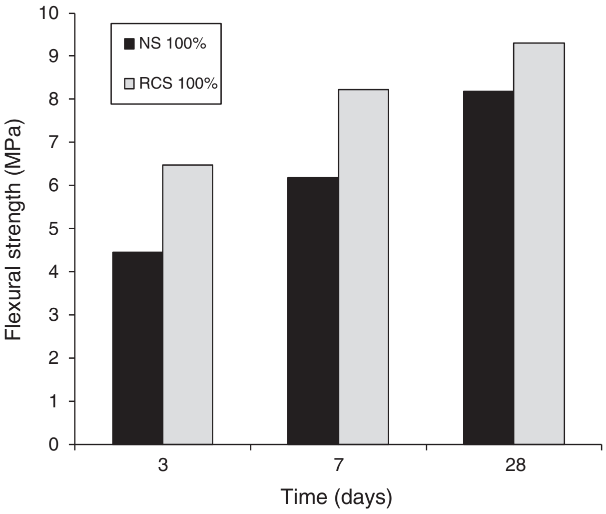

Fig. 13. Flexural strength of sand replacement mortar, for standard mortars made according to EN 196-1 using Norm sand (100% NS) and replacement of 100% of the sand with RCS (see also Table 7).

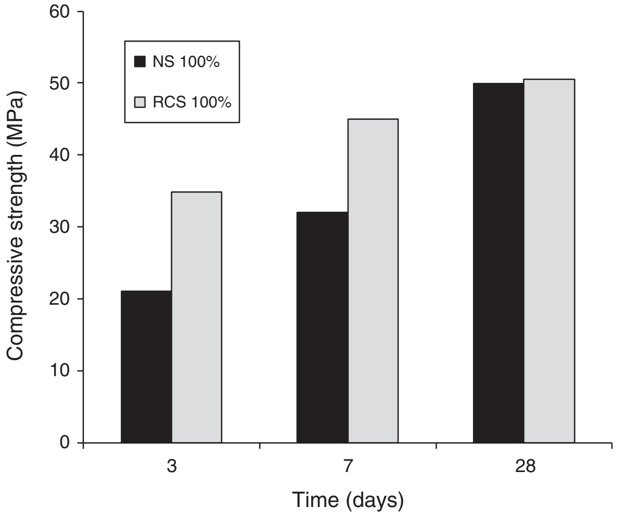

Fig. 14. Compressive strength of sand replacement mortar, for standard mortars made according to EN 196-1 using Norm sand (100% NS) and replacement of 100% of the sand with RCS (see also Table 7).

provide supplementary nucleation sites for the hydration of the cement, thus accelerating the process. The higher compressive strength can be attributed to the partial re-hydration of the hardened cement paste fraction of the RCS, which can also be activated by the high pH provided by the cement hydration.

9. Conclusions and discussion

In this research, laboratory made concrete with known composition 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 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, XRD patterns, XRF composition and SEM-EDX images. 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. The XRF and XRD tests confirmed the decrease of SiO_2 content with particle size.

A new method of quantifying the α-quartz content of the samples using the calibrated DSC signal was developed. The method was proven to be accurate by comparing with XRF results, and also following the trend indicated by XRD. The SEM-EDX technique provided further information on the morphology of the particles, which explains the particle size distributions of the finer fraction.

When comparing the α-quartz 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.

Recycled concrete sand (RCS) was tested to replace 100% of the Norm sand in standard mortars. A significant decrease of fresh mortar spread was observed; however, with the addition of 1% superplasticizer by weight of cement, the mortar sample obtained flowability. The mechanical performance of the RCS test was very promising. The RCS mortar samples obtained higher strength than the reference samples, especially for the early strength. The 3, 7 and 28 days flexural strengths increased by 45.3%, 33.2% and 13.7% respectively, compared to the reference mortar. The 3 and 7 days compressive strength increased by 65.6% and 40.3%, respectively. However, the 28 days compressive strength increased only by 1.1%, indicating that the positive effect of RCS is manifested mostly at early ages.

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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Corrigendum

Corrigendum to 'Properties of various size fractions of crushed concrete related to process conditions and re-use'
[Cement and Concrete Research 52 (2013) 11–21]

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The authors would like to update a few lines in the section 'Introduction' of the published article.

After the last sentence of the penultimate paragraph the authors would like to add the sentence "The above literature review can also be found in [21]." Also, the last paragraph of the Introduction should end with a reference, and should read as "new concrete production [21]". For the remaining part of the paper these changes have no further implications.

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[1] The authors would like to apologise for any inconvenience caused.

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