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Recycled concrete fines and aggregates- the composition of various size fractions related to crushing history

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. Even if the soil and some other wastes were excluded, the annual C&DW generation is computed at almost 500 kg per person within the EU. 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. The UK went from using only 10% recycled materials in 1989, to 25% in 2001. C&DW in England and Scotland make up about 66% and 50% of recycled aggregates, respectively. The Scottish Executive Development Department (SEDD) found that the total estimated quantity land filled was composed of 44% mixed C&DW, clean soil (34%), contaminated soil (13%), and contaminated C&DW and asphalt (9%). From these, 19% of the mixed C&DW was subsequently reused/recycled.

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 accounts 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, published in 2008, from WBCSD [2]).

Oikonomou [1] also presents data for the US and Japan. In the US, the aggregates used can be divided by use in pavements (10-15%), other road construction and maintenance work (20-30%) and structural concrete (60-70%). Recycled aggregates are produced by natural aggregates producers (50%), contractors (36%) and debris recycling centers (14%). In Japan, the concrete recycling ratio reached 96% in 2006, from only 48% in 1990, and it is mostly used as sub-base material in road construction.

Recycled concrete aggregates (RCA) are mainly used as road-base material, but another interesting application would be their incorporation into concrete mixes. Moreover, through an efficient crushing and milling technique, recycled concrete can be a beneficial addition [3,4]. This study deals with the mineralogical composition of several recycled concrete fractions, obtained through two crushing methods.

Materials

A concrete recipe was designed in order to link the initial constituents of concrete to the composition of the recycled material. The recipe (in % mass) consisted of 14.5% CEM I

42.5 N, 1.7% limestone powder, 30.7% sand (N1), 28.2% gravel 0-4 (G1), 17,5% gravel 2-8 (G2) and 7.3% water. 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 RCA I throughout this study. Through sieving the following fractions were obtained: < 150 μm (termed RCA I 0-150), 150- 250 μm (termed RCA I 150-250), 250-300 μm (termed RCA I 250-300), 300-500 μm (termed RCA I 300-500), 500 μm – 1 mm (termed RCA I 500-1), 1-2 mm (termed RCA I 1-2), 2-4 mm (termed RCA I 2-4), 4-6 mm (termed RCA I 4-6), 6-8 mm (termed RCA I 6-8), 8-11.2 mm (termed RCA I 8-11.2), 11.2-16 mm (termed RCA I 11.2-16) and 16-32 mm (termed RCA I 16-32).

The prototype Smart Crusher, termed Smart Crusher 1 (SC 1) was used to crush concrete samples from the same batch as previously crushed using the conventional jaw crusher. The material was pre-crushed, using the smart crusher at its maximum opening size, in order to simulate the pre-crushing that recycled concrete is submitted to on a larger scale. After that, the material was smart-crushed, sieved on the 2 mm sieve and particles larger than 2 mm were returned to the crusher, in order to maximize the production of fines. The procedure was repeated, and the obtained material was afterwards sieved into fractions. The following fractions were obtained: : < 63 μm (termed SC 1 0-63), 63- 125 μm (termed SC 1 63-125), 125- 200 μm (termed SC 1 125-200), 200- 250 μm (termed SC 1 200-250), 250-300 μm (termed SC 1 250-300), 300-500 μm (termed SC 1 300-500), 500 μm – 1 mm (termed SC 1 500-1), 1-2 mm (termed SC 1 1-2), 2-4 mm (termed SC 1 2-4), 4-5.6 mm (termed SC 1 4-5.6), 5.6-8 mm (termed SC 1 5.6-8), 8-11.2 mm (termed SC 1 8-11.2), 11.2-16 mm (termed SC 1 11.2-16) and 16-22.4 mm (termed SC 1 16-22.4).

Particle size distributions

Figure 1 shows the particle size distribution of RCA I and SC 1. A first observation is that the SC 1 produces much more fine material when compared to the conventional crusher. A more interesting fact is that, using this method of crushing, the PSD of the obtained material is very close to the one of the initial mix, especially in the aggregate size range (over 0.5 mm). This is an indication that the Smart Crusher 1 indeed separates the initial, clean aggregates from the cement paste. It can be seen that, using the SC 1 crusher, the volume of the fraction under 1 mm of the recycled concrete is 5 times higher than the one generated by the conventional crusher. Considering the fraction under 0.5 mm, the SC 1 produced over 5 times more fines than the conventional crusher, generating the same volume of fines as were used in the original mix.

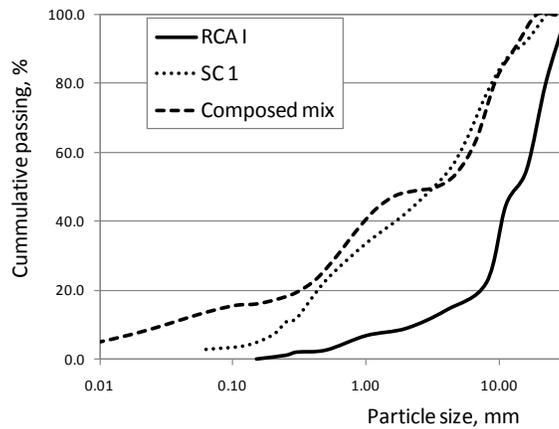


Figure 1. PSD of the two crushed materials, RCA I, SC 1 and initial mix.

Thermal analysis

For all fractions of both RCA I and SC 1, the thermal analysis was performed using a Netzsch STA F1. Both thermogravimetric (TG) and differential thermal analysis (DSC) were performed. As an example, Figure 2 shows the TG-DSC analysis results of SC 1 300-500 μm .

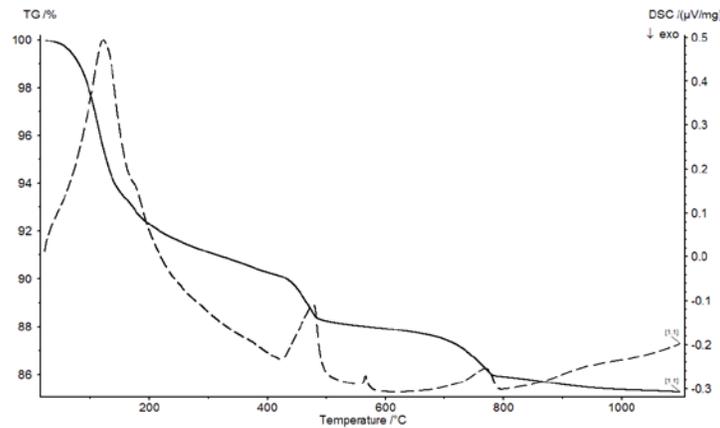


Figure 2. TG-DSC analysis of SC 1 300-500 μm .

The TG analysis is used to determine the mass loss of the sample with the variation of temperature. The temperatures at which these mass loss effects occur are associated with the presence of certain compounds within the sample [5, 6].

The DSC curve registers any thermal reaction (exo- or endothermic) which takes place within the sample and are usually associated with a mass change. However, there are reactions which take place without any mass change, but for which thermal effects can be observed. These can also be phase transitions (like melting or solidifying of materials) but

also structural changes (from one crystallographic form of a compound to another, which takes place with the adsorption or release of energy). In Figure 2, such an effect can be observed at approx. 570 °C. These effects are quantified using the height of the peak or the area under it- both measurements being proportional to the concentration of the respective compound within the sample.

A transformation is registered at ~570 °C : the phase transition of α -SiO₂ to β -SiO₂. The peak area at 560-575 °C was quantified on the DSC curve for all analyzed samples, together with the same measurements performed on the sand used in the concrete mix. The N1 sand used in all mixes was shown to be constituted of 98% SiO₂ by XRF measurements, while the G1 and G2 aggregates contained 96-97% SiO₂. Therefore, the calibration curve is also valid for the used gravels and the combination of aggregates used in this study. The three aggregate types used in the mix design are considered to have the same composition. These ratios can be used as a measure of the SiO₂ content of each fraction. A calibration curve was realized for different contents of sand (0-80% in a pure hardened cement paste matrix and 100% sand sample), in order to decrease the measurement error. Figure 3 shows this calibration curve and the equation used to compute the SiO₂ content of all considered samples.

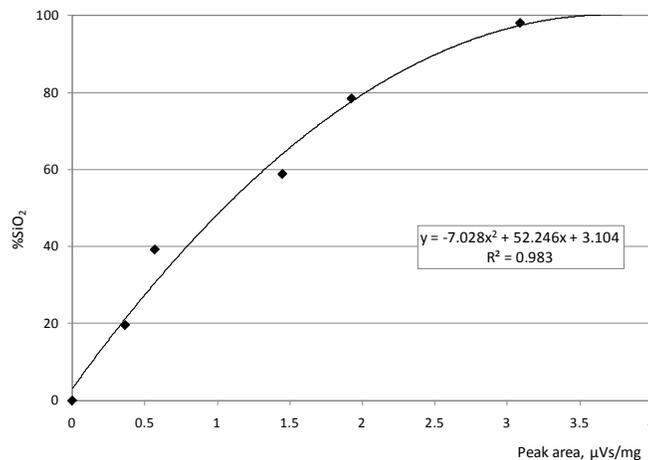


Figure 3. Calibration curve for a sand-cement paste mixtures using DSC measurements.

The highest particle sizes of RCA I shown in Figure 4 are represented differently, because these samples have an estimated, not measured, SiO₂ percentage. This is due to insufficient samples from the RCA I crushing, which could not give a statistically significant measurement, but the trend has been extrapolated based on other crushing experiments using the same material and the same conventional crusher. These samples will be produced again, in order to validate the trend and to show exact values of the α -SiO₂ content determined through the DSC measurements. In Figure 4, particle size is taken to be the maximum size of the fraction (for instance RCA 2-4 mm will be represented at 4 mm).

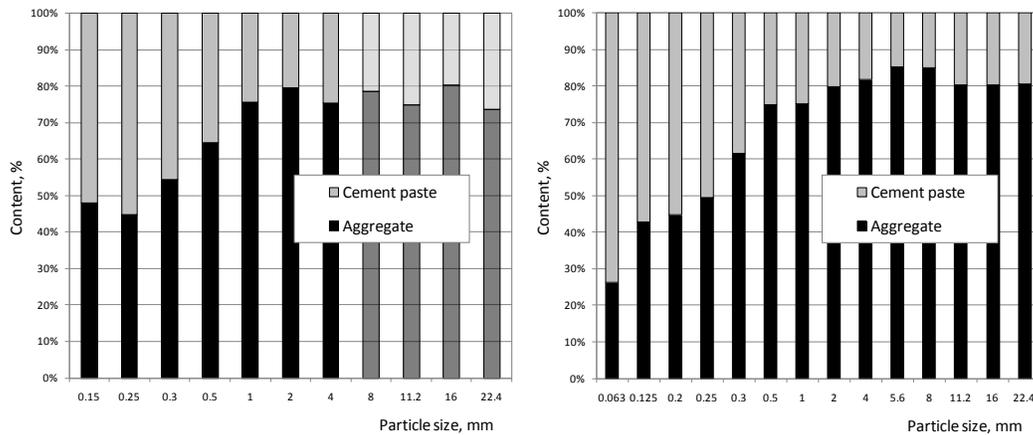


Figure 4. Distribution of aggregate and cement paste in mass % in RCA I (left) and SC 1 (right)

The SC 1 samples show much lower contents of SiO_2 in the finest fractions than RCA I. The finest SC 1 fraction, below $63 \mu\text{m}$, contains approx. 27% SiO_2 , while the $63\text{-}125 \mu\text{m}$ fraction contains approx. 42 % SiO_2 , as opposed to RCA I $0\text{-}150 \mu\text{m}$, which contains approx. 48% SiO_2 . This data, combined with the higher amount of fines generated by SC 1 (see Figure 1), shows that a higher amount of the cement paste fines can be recovered using the SC 1 when compared to the conventional crusher. The increase in the content of cement paste (from 52 to 73%, so an increase of almost 50%), coupled with the volume increase shown in Figure 3, means that 7.5 times more cement paste is separated using the SC 1. This also suggests that larger particles generated in the “smart crushing” process will be almost free of attached cement paste. Already from the $300\text{-}500 \mu\text{m}$ fraction, it can be seen that SC 1 has a 75% SiO_2 content, compared to 65% in RCA I. The mass content of the SiO_2 aggregates in the concrete mix is 76%, which means that particles above 2 mm are enriched in quartz, just like the small particles contain much more than the 25% of cement paste which is contained in the total concrete mass. A further analysis of the SC 1 samples can be found in [7].

Density measurements

Density measurements were performed on all 14 samples obtained from SC 1, using a Micromeritics AccuPyc 1340 helium pycnometer. The results were correlated with the SiO_2 content estimated based on the DSC. Figure 5 shows the density of the samples (right y-axis) on the same graph with the SiO_2 contents (left y-axis).

Figure 5 shows a very good agreement between the density and α -quartz content of all SC 1 fractions. This validates again the SiO_2 estimation obtained from the DSC results. Moreover, the agreement suggests that density measurements can be used as a faster control method for the quartz content of the recycled concrete fractions [7].

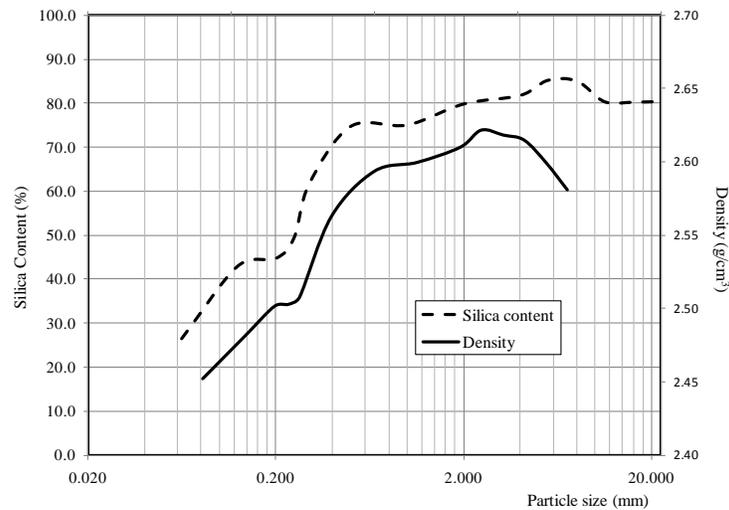


Figure 5. Density (g/cm³) and SiO₂ content (%) of all analyzed SC 1 samples.

Ordinary Portland cement replacement

Recycled concrete fines (RCF) smaller than 150 μm were used to replace cement in mortar samples. The replacement ratios are 10%, 20% and 30% by mass of cement, with the increasing replacement ratio, different dosages of Glenium 51 were used to keep the same workability as the reference sample [7], which was mixed according to EN 196-1 (450 g cement : 1350 g norm sand : 225 g water) [8].

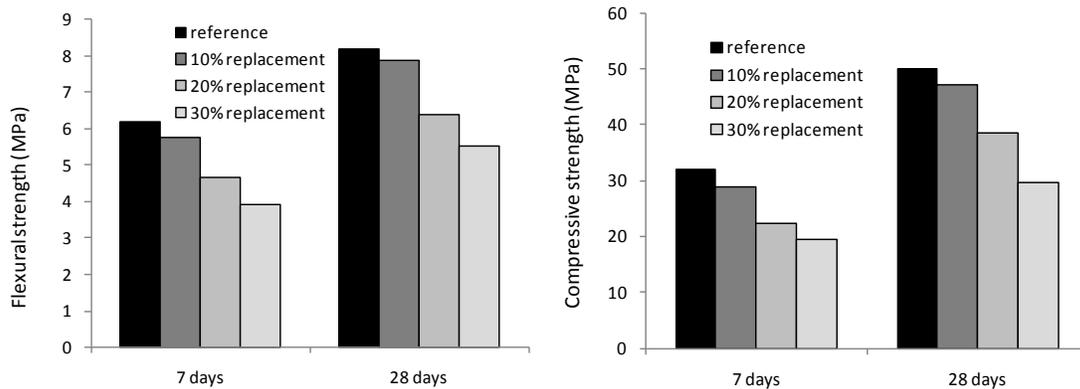


Figure 6. Flexural (left) and compressive strength (right) of OPC replacement.

The flexural strength and compressive strength results (obtained according to the same standard) are illustrated in Figure 6. It can be seen that, by replacing cement by RCF, the flexural strengths decrease with the increasing replacement ratio. A 10% replacement of cement by RCF reduces the 28 days flexural strength by only 3.9%, while 20% replacement

reduces the 28 days flexural strength by 21.9%. As can be seen in Figure 6 (right), using RCF to replace cement in mortar reduces the compressive strengths. By replacing 10% of cement, the 28 days compressive strength is reduced only by 5.9% which means RCF has a certain degree of binding effect in the mixture; this can be caused by the unhydrated cement present in the RCF. By replacing 20% of cement by RCF, the 28 days compressive strength reduces by 22.67%. This can be caused by the high water absorption of RCF; the same explanation can be used for 30% replacement. This effect is also in line with observations from literature [3, 4].

From the experiment results, it can be concluded that all the replacement ratios will reduce both of the 7 days and 28 days strengths. RCF has a beneficial effect when replacing 10% of the cement, since the strength has decreased with just under 6% (so less than the replacement level).

Conclusions

A concrete recipe was designed using CEM I 42.5, limestone and three types of aggregates. The obtained concrete specimens were crushed using a conventional jaw crusher, as well as the smart crusher SC 1. Two materials were obtained: RCA I, after crushing the concrete specimens using the commercial jaw crusher, and SC 1, after crushing using the smart crusher prototype. Each of these materials was then divided into fractions according to their particle size. All these fractions were then thermally characterized by their mass loss at certain treatment temperatures.

For the finer fractions, TGA and DSC were performed using a Netzsch STA F1. The DSC results were used to determine the content of aggregate in each fraction. These results have shown a much higher cement paste content in the finer fractions obtained from the SC, as opposed to the conventional jaw crusher. The recovery of the cement paste, in the same particle size range, was improved by 50%. This information becomes important when it is also correlated to the particle size distribution of the fractions obtained through the two methods. Sieving the two materials (RCA I and SC 1) 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 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 -SiO₂ than the ones from the RCA I series. The SC 1 fines contained a maximum of 27% α -SiO₂ in the 0-63 μ fraction and under 42% in the 63-125 μ m, as opposed to approx. 50% in the finest fraction obtained from RCA I.

The density measurements of all obtained fractions have shown an excellent correlation with their α -quartz content, validating the measurements.

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