

## **Smart crushing of concrete and activation of liberated concrete fines**

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## Abstract

Recycling of construction and demolition waste (C&DW) is one of the important topics in concrete research nowadays. For the EU, it is estimated that the annual generation of C&D waste is the largest single waste stream, apart from agricultural waste. Recycled concrete aggregates (RCA) are mainly used for road construction, 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.

This study deals with the mineralogical composition of several recycled concrete fractions, obtained through various crushing methods (a conventional jaw crusher and a smart crusher laboratory prototype). The finer fractions were analyzed in terms of particle size distribution and density. All fractions were then thermally characterized by their mass loss at certain treatment temperatures. DSC results were used to determine the content of aggregate in each fraction. Estimations were made for the composition of all RCA fractions, in terms of hydrated cement paste and crushed aggregates content. XRD measurements were used in order to follow the variation in mineralogical composition between the fractions. XRF measurements were done for validation. A thermal treatment was used to activate the recycled concrete fines (RCF). Calorimetric tests were used to estimate the reactivity of the RCF. The use of both RCF and RCA was then investigated in mortar and concrete recipes, using fresh and hardened state tests.

The optimization of the crushing method of recycled concrete is evaluated and discussed. The smart crushing method was found to produce much more recycled concrete fines and cleaner aggregates than a conventional crusher. Moreover, the  $\alpha$ -quartz amount of the recycled concrete fines was found to be significantly lower than the one obtained using a commercial jaw crusher. The mortar tests showed the suitability of recycled concrete fines as cement replacement in both CEM I and blended cements recipes. The use of recycled concrete aggregates as a 100% replacement of Norm sand was also tested successfully.

## Introduction

Recycling of construction and demolition waste (C&DW) is one of the important topics in concrete research nowadays. Oikonomou (2005) 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 earth 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% to 90% of their C&D waste production. In the Netherlands, Germany and Denmark landfilling has become more costly than recycling.

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. This study deals with the mineralogical composition of several recycled concrete fractions, obtained through two crushing methods.

As is known that the concrete recycling plants are mainly targeting to harvest the recycled concrete aggregates from the waste concrete. Recycled concrete fines (RCF) are considered as by-product which are mainly generated during the crushing and sieving process. RCF

contains mostly  $\alpha$ -quartz originated from broken aggregates and hardened cement paste. The chemical composition of RCF is similar to that of cement. RCF are considered as the waste by Hansen (1992). In the vision of total concrete recycling, some researchers suggested to use RCF as the raw material for cement manufacturing (Shima et al., 2005; Mulder et al., 2007). However, relevant information of re-linking RCF was not found yet.

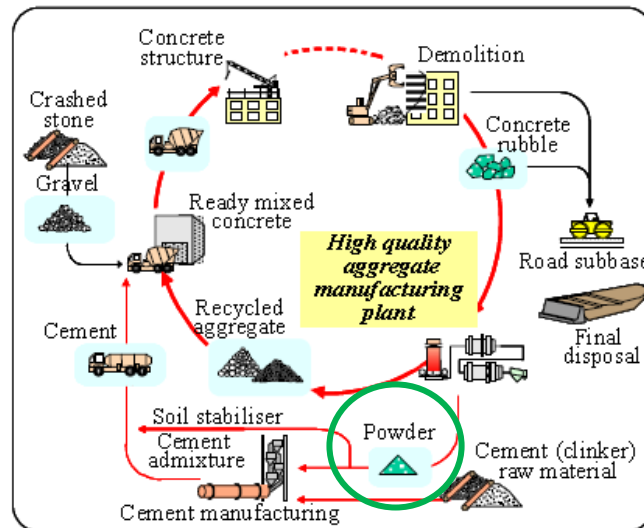


Figure 1. The vision of total concrete recycling proposed by Shima (2005)

It is found by Shui (2008; 2009; 2011) that dehydrated cement paste has the properties of recovering back to the original hydration products. The rehydrated dehydrated cement paste was found to have gained mechanical strength depending on the dehydration temperature. It was also demonstrated that dehydrated cement paste mixed with fly ash with certain Ca/Si ratio had good activation effect (Shui et al., 2011). The principle difference between RCF and pure cement paste is the existence of  $\alpha$ -quartz in RCF. The cement paste portion of RCF should have identical effect after dehydration as the dehydrated cement paste. This research is intended to use thermal treatment to dehydrate the cement paste portion in RCF in order to use RCF as cement replacement material.

## I. Materials and mix design

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 using mass balances. The final objective is to be able to describe the composition of recycled concrete particles through simple physical analysis, and establishing some concepts that make knowing the initial composition less critical.

The PSD of the cement and limestone was determined using the Mastersizer 2000 Particle Analyzer. The PSD of the three aggregate types (a 0-4 mm sand termed S1 and two gravel types, a 2-8 mm termed G1 and an 8-16 mm termed G2) were determined through dry sieving. Figure 2 shows the cumulative distributions for all materials, the designed target line and the particle size distribution of the final mix.

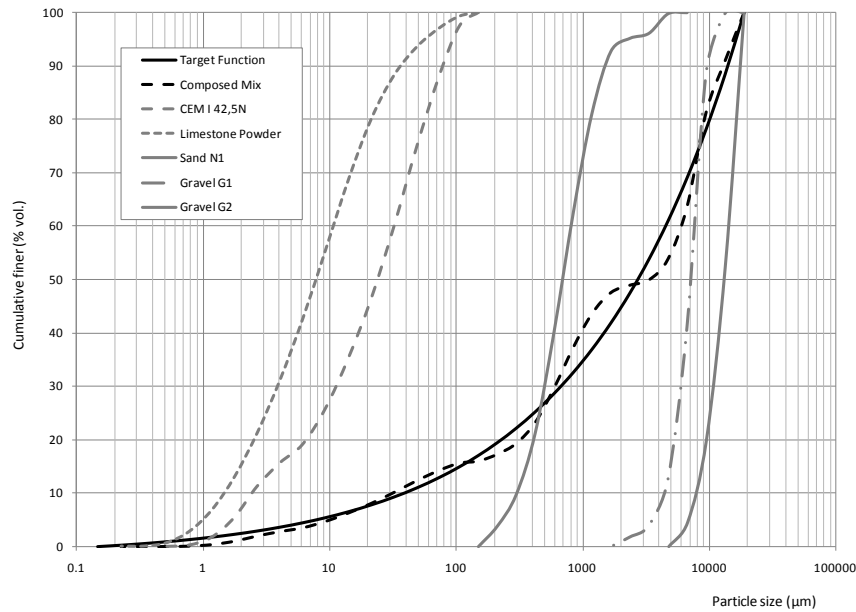


Figure 2. PSD of all used materials, the target function and the composed mix

## II. Crushing of the concrete specimens

### 1. Conventional jaw crusher

The crushing of the concrete samples was performed after 91 days from the day of casting, when the measured compressive strength of the samples reached 60.5 MPa. 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  $\mu\text{m}$  (termed RCA I 0-150), 150- 250  $\mu\text{m}$  (termed RCA I 150-250), 250-300  $\mu\text{m}$  (termed RCA I 250-300), 300-500  $\mu\text{m}$  (termed RCA I 300-500), 500  $\mu\text{m}$  – 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).

### 2. Smart crusher (SC 1)- a laboratory-scale prototype

The prototype, laboratory-scale Smart Crusher, termed Smart Crusher 1 (SC 1) of Schenk Concrete Consultancy was used to crush concrete samples from the same batch as previously crushed using the conventional jaw crusher. This crushing step was performed after a much longer curing time of the samples, so their compressive strength was also increased. The material was precrushed, using the smart crusher at its maximum opening size, in order to simulate the precrushing that recycled concrete is submitted to on a larger scale. After that, the material was smart-crushed, sieved on the 2 mm sieve and everything larger than 2 mm returned to the crusher, in order to maximize the production of fines. The procedure was repeated, for a total of 2 returns to the crusher of the material above 2 mm. The obtained material was afterwards sieved into fractions, using more sieves to divide the fines than for

the material RCA I, in order to better see the properties of the generated fines. The following fractions were obtained:  $< 63 \mu\text{m}$  (termed SC 1 0-63),  $63-125 \mu\text{m}$  (termed SC 1 63-125),  $125-200 \mu\text{m}$  (termed SC 1 125-200),  $200-250 \mu\text{m}$  (termed SC 1 200-250),  $250-300 \mu\text{m}$  (termed SC 1 250-300),  $300-500 \mu\text{m}$  (termed SC 1 300-500),  $500 \mu\text{m} - 1 \text{ mm}$  (termed SC 1 500-1),  $1-2 \text{ mm}$  (termed SC 1 1-2),  $2-4 \text{ mm}$  (termed SC 1 2-4),  $4-5.6 \text{ mm}$  (termed SC 1 4-5.6),  $5.6-8 \text{ mm}$  (termed SC 1 5.6-8),  $8-11.2 \text{ mm}$  (termed SC 1 8-11.2),  $11.2-16 \text{ mm}$  (termed SC 1 11.2-16) and  $16-22.4 \text{ mm}$  (termed SC 1 16-22.4).

Figure 3 shows the particle size distribution of RCA I and SC 1.

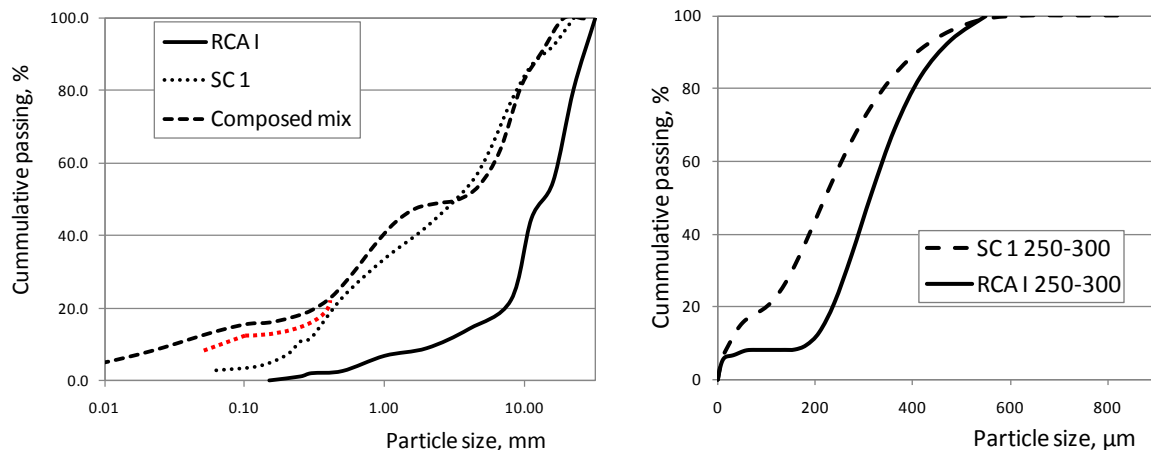


Figure 3. PSD of the two crushed materials, RCA I and SC 1 (complete PSD, left) and RCA I 250-300  $\mu\text{m}$  and SC 1 250-300  $\mu\text{m}$  (right).

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 materials used to produce the concrete, 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 hydrated cement fines. 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, bringing the PSD to the same volume as the initial fines that the mix was composed of. The red dotted line represents a theoretical crushing curve of the fines, in the ideal case in which fines are not lost during the crushing. In the case of both the conventional crusher and SC1, the very fine particles are lost (mainly as dust) as indicated by the red arrows in Figure 4, but this effect can be avoided in a future crusher model.

Figure 3 (right) confirms this explanation, showing that, even though the minimum and maximum particle size of each fraction of RCA I and SC 1 are the same, the distribution is shifted towards smaller particles. In the case of RCA I 250-300  $\mu\text{m}$  and SC 1 250-300  $\mu\text{m}$ , it can be seen that 50% of the particles are under 240 and 310  $\mu\text{m}$  respectively.

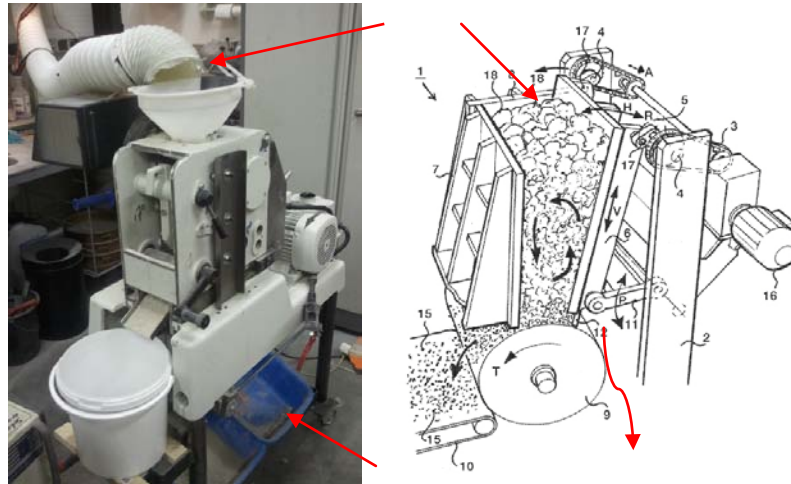


Figure 4. Picture of the SC1 lab model (left) and scheme of the scaled-up SC prototype (right)

The four finest fractions were analyzed using the Mastersizer 2000 by laser granulometry. 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 RCA I and SC 1 are presented in Table 1.

Table 1.  $d_{0.1}$ ,  $d_{0.5}$  and  $d_{0.9}$  measured for the four finest fractions of RCA I and SC 1

	$D_{\min}$ [ $\mu\text{m}$ ]	$D_{\max}$ [ $\mu\text{m}$ ]	$d_{0.1}$ [ $\mu\text{m}$ ]	$d_{0.5}$ [ $\mu\text{m}$ ]	$d_{0.9}$ [ $\mu\text{m}$ ]
<b>RCA I 0-150</b>	0.955	208.930	10.9	68.5	169.2
<b>RCA I 150-250</b>	91.201	478.630	134.8	212.8	334.1
<b>RCA I 250-300</b>	138.038	630.957	212.7	310.5	450.3
<b>RCA I 300-500</b>	208.930	831.764	287.1	459.2	720.4
<b>SC 1 0-63</b>	0.63	208.93	7.585	69.183	138.03
<b>SC 1 63-125</b>	0.478	120.22	5.754	22.908	60.255
<b>SC 1 125-200</b>	0.63	316.23	17.378	104.71	208.93
<b>SC 1 200-250</b>	0.724	478.63	19.953	158.49	316.23
<b>SC 1 250-300</b>	0.832	630.96	26.303	239.88	416.87

The analysis confirmed the smaller particle size of SC 1. 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 RCA I and SC 1 fractions sieved between the same sizes are comparable. SC 1, however, consistently has a lower  $D_{\min}$  than the corresponding RCA I fractions. In the case of  $D_{\max}$ , when compared to the corresponding

RCA I fraction, it can be seen that the value is in all cases almost the same. This suggests that the SC 1 fractions have more acicular-shaped particles, which can pass vertically through a sieve, even though they have one dimension which is much higher than the sieve size. This hypothesis will be verified using scanning electron microscopy (SEM). Moreover, SC 1 has a narrower range, which is also seen from the  $d_{0.1}$ ,  $d_{0.5}$  and  $d_{0.9}$  values, and the particles are closer to the smaller dimensions of the fraction ( $d_{0.5}$  for instance is consistently much lower).

### III. 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 (DTA) were performed. As an example, Figure 5 shows the TG-DTA analysis results of SC 1 300-500  $\mu\text{m}$ .

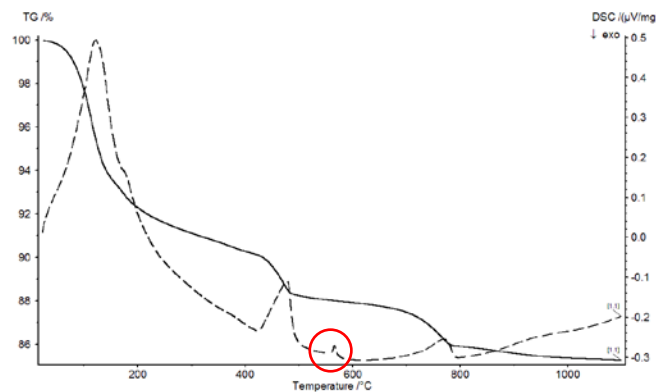


Figure 5. TG-DTA analysis of SC 1 300-500  $\mu\text{m}$ .

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.

The DTA curve registers any thermal reaction (exo- or endothermic) which takes place within the sample. These are usually associated with a mass change (Table 2).

Table 2. Transformations that can take place when cement paste is subjected to a thermal treatment as a function of temperature

Temperature	Transformation
<110 ° C	Loss of physically bound water
155-170 ° C	Dissociation of gypsum
~450 ° C	Dissociation of portlandite
~850 ° C	Dissociation of carbonates
~1050 ° C	Loss of chemically bound water



However, there are reactions which take place without mass change, but for which thermal effects can be observed. These are usually phase transitions (like melting or solidifying of materials) or phase transitions (from one crystallographic form of a compound to another, which takes place with the adsorption or release of energy). In Figure 5, 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. Again, the first derivative of the curve is used to show any peak which might not be obvious on the initial DTA curve.

A transformation is registered at ~570 °C : the phase transition of  $\alpha$ -SiO<sub>2</sub> to  $\beta$ -SiO<sub>2</sub>. 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% SiO<sub>2</sub> by XRF measurements, while the G1 and G2 aggregates contained 96-97% SiO<sub>2</sub>. The three aggregate types used in the mix design are considered to have the same composition.

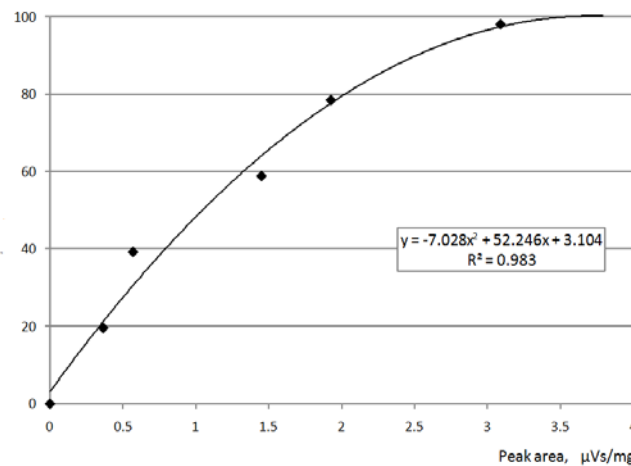


Figure 6. Calibration curve for sand-cement paste mixtures using DSC measurements.

These ratios can be used as a measure of the SiO<sub>2</sub> 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 6 shows this calibration curve and the equation used to compute the SiO<sub>2</sub> content of all considered samples.

The highest particle sizes of RCA I shown in Figure 7 are represented differently, because these samples have an estimated, not measured, SiO<sub>2</sub> 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  $\alpha$ -SiO<sub>2</sub> content determined through the DTA measurements.

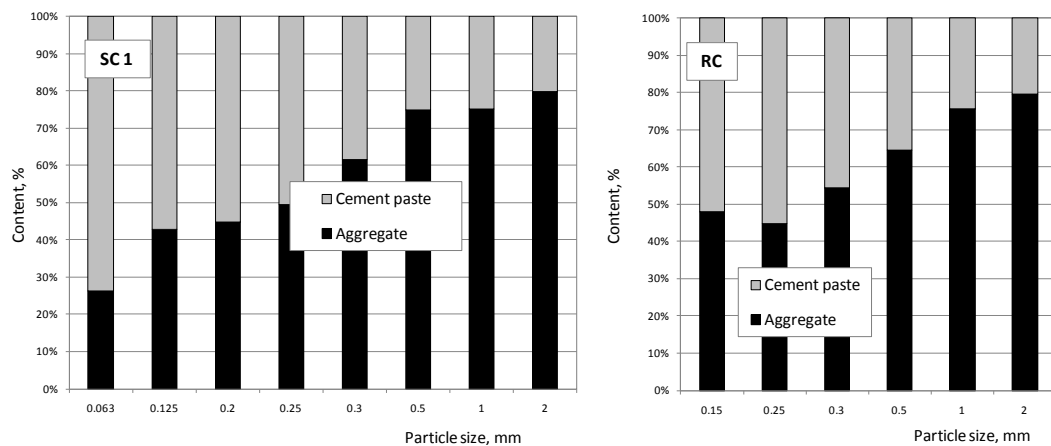


Figure 7. Distribution of aggregate and cement paste in RCA I (left) and SC1 (right)

The SC 1 samples show much lower contents of  $\text{SiO}_2$  in the finest fractions than RCA I. The finest SC 1 fraction, below 63  $\mu\text{m}$ , contains approx. 27%  $\text{SiO}_2$ , while the 63-125  $\mu\text{m}$  fraction contains approx. 42 %  $\text{SiO}_2$ , as opposed to RCA I 0-150  $\mu\text{m}$ , which contains approx. 48%  $\text{SiO}_2$ . This data, combined with the higher amount of fines generated by SC 1 (see Figure 3), 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 will be almost free of attached cement paste. Already from the 300-500  $\mu\text{m}$  fraction, it can be seen that SC 1 has a 75%  $\text{SiO}_2$  content, compared to 65% in RCA I. The content of the  $\text{SiO}_2$  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.

Table 3. Oxide composition of RCF 63-125 (determined by XRF) and comparison with the composition of ENCI CEM I 42.5 N

Oxide	ENCI CEM I 42.5 N	RCF
$\text{Al}_2\text{O}_3$	5.0	3
$\text{SiO}_2$	20	52
$\text{SO}_3$	2.2	<1
$\text{CaO}$	63.0	36
$\text{Fe}_2\text{O}_3$	3.0	2

The oxide composition of RCF was determined by X-Ray fluorescence (XRF). The silica content in Table 3 is a sum of both  $\alpha$ - and the silica incorporated into the cement hydration products (approximately 20% of the mass of hydration products consists of silica thettraedra).

#### IV. Density measurements and thermal treatment

Density measurements were performed on samples obtained from SC 1, using a helium pycnometer. The results were correlated with the  $\text{SiO}_2$  content estimated based on the DTA. Figure 8 shows the density of the samples (right y-axis) on the same graph with the  $\text{SiO}_2$  contents (left y-axis).

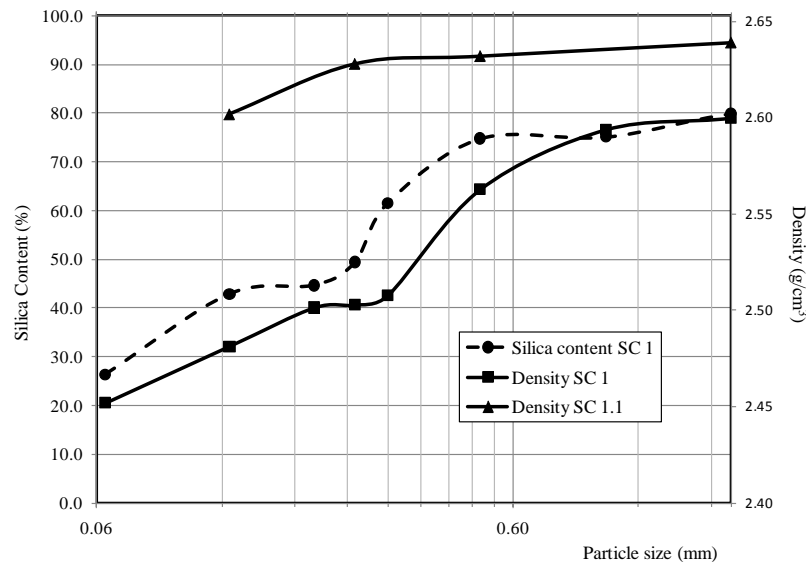


Figure 8. Density ( $\text{g/cm}^3$ ) and  $\text{SiO}_2$  content (%) of all analyzed SC 1 samples

Figure 8 shows a very good agreement between the density and  $\alpha$ -quartz content of all SC 1 fractions. This validates again the  $\text{SiO}_2$  estimation obtained from the DTA 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.

Because of the insufficient accuracy of the sieving step (see Table 1), a new series of samples were prepared for density tests. The jaws of the SC 1 were slightly modified in order to have a better thermal insulation (particles are dried better while crushing) and to ensure a decreased space velocity of the particles in the crusher (higher time in the machine). This modified SC is termed SC 1.1. Concrete was crushed again using the SC 1.1, and all material above 2 mm brought back to the SC 1.1 four times, while using a vacuum cleaner to remove all the generated dust that would otherwise be left in the powders. The obtained densities of these samples can also be observed in Figure 8. The maximum density of 2.6529 in Figure 8 corresponds to pure norm sand. Based on the obtained densities from the SC 1.1, it can be estimated that the  $\alpha$ - $\text{SiO}_2$  content of the fractions was increased up to  $\sim 94\%$  for the fraction 1-2 mm, which would be almost clean sand (which has a  $\alpha$ - $\text{SiO}_2$  content of 98%).

In order to verify that a thermal treatment will not affect the PSD of the recycled concrete fines (RCF) significantly, a grinding test was performed (Figure 9). Samples of cement paste with a high water/cement ratio and long mixing time were made, in order to ensure a degree of hydration close to unity. The samples were kept under water for 6 months and then crushed and sieved. The fraction 2-4 mm was selected for the grinding experiments. The samples were then dried in an oven at 110, 400, 600 and 800 degrees Celsius. All these samples, together with a room temperature one (termed rt) were ground under the same

conditions (grinding time, number of runs, scraping etc) and the result analyzed using a laser diffractometer. The results (cumulative PSD) are shown in Figure 9 (left).

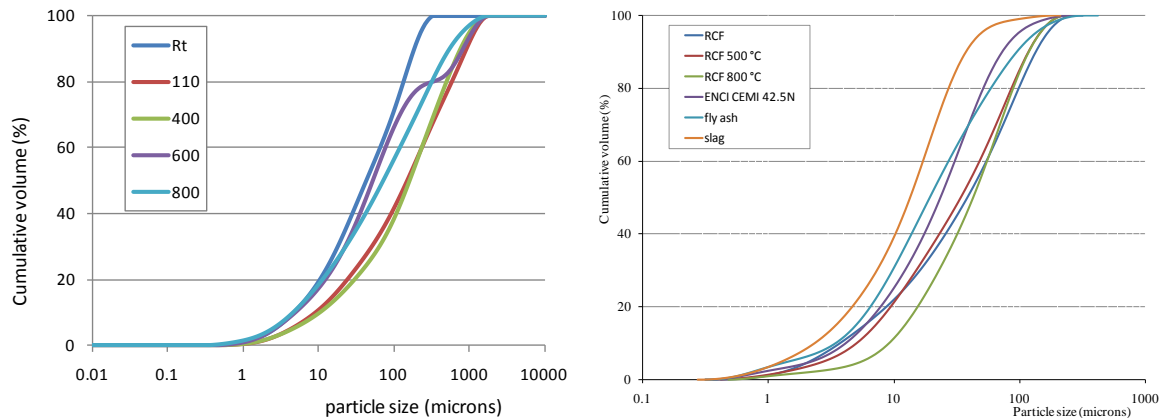


Figure 9. PSD of thermally treated cement paste (left) and thermally treated RCF and reference materials (cement, slag, fly ash) (right).

It can be observed that the room temperature sample achieved the finest PSD. However, no significant difference was found between the samples, except a low tendency to agglomerate for the RCF treated at 110 and 400 degrees Celsius. The samples treated at higher temperatures (600 and 800 degrees Celsius) benefited from the volume expansion due to the transformation between  $\alpha$ - and  $\beta$ -quartz, and therefore show a PSD very close to the original one.

## V. Use of recycled concrete fines as cement replacement

The intention of this research is to apply RCF in new concrete production. There are several factors that can affect the compressive strength test results: cement type, water cement ratio, specimen size, mould type, the specimen surface, curing conditions, type of testing machine, the stress rate, etc. (Neville, 2002). Mortar samples were tested by following the European standard EN 196-1 to keep the constant test conditions. The recipe for the standard mortar test is shown in Table 4. RCF treated with different temperatures were used to replace part of cement in the standard mortar sample.

### V.1. Ordinary Portland Cement replacement test

Untreated RCF, 500 °C treated RCF and 800 °C treated RCF (all containing approx. 70% hardened cement paste and 30%  $\alpha$ -SiO<sub>2</sub>) were used to replace 10%, 20% and 30% of cement in the standard mortar sample. PKVA fly ash (a standard coal combustion fly ash used in blended cement in the Netherlands) was also used to replace the same amount of cement. EN 196-1 standard mortar was made as the reference. 7 days and 28 days flexural strength and compressive strength were tested to measure the mechanical strength development. The mix proportioning of the tested mortars is given in detail in Table 4. The term replacement material in Table 4 means untreated RCF, 500 °C treated RCF, 800 °C treated RCF or PKVA fly ash. The consistence of the fresh mortar samples was determined by using the flow table test according to EN 1015-3. Original and thermally treated RCFs have higher water absorption than that of cement. The spread values of the mortar samples replacing 20% and 30% of cement has decreased significantly. In order to obtain similar spread as the reference

mortar, superplasticizer (Glenium 51) was used for the RCF 20% replacement and 30% replacement samples. The PSDs of all fines can be seen in Figure 9 (right).

Table 4. Mix proportioning of the tested mortars used for cement replacement by thermally treated RCF.

Material	EN 196-1 (g)	10% Replacement (g)	20% Replacement (g)	30% Replacement (g)
Norm sand	1350	1350	1350	1350
CEM I 42.5 N	450	405	360	315
Replacement material	0	45	90	135
Water	225	225	225	225

The data depicted in Figure 10 show the spread of the mortar samples depending on the RCF content.

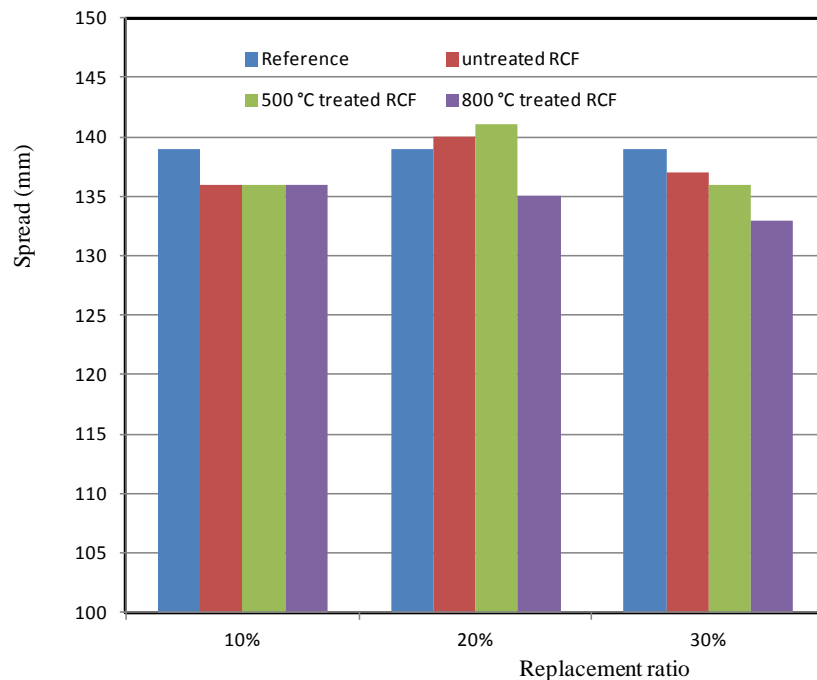


Figure 10. Spread of fresh mortars containing thermally treated RCF ( 500 °C RCF sample + 0.12% SP and 800 °C RCF sample + 0.24% SP).

It can be seen from Figure 10 that all the RCF replacement mortar samples obtained similar spread values as the reference mortar. Both the untreated RCF and thermally treated 10%

RCF replacement mortar samples have lower spread values than the reference mortar. It can be calculated that the application of RCF in mortar samples increases the water demand and thus decreases the fresh mortar spread. In order to achieve the same spread values, 0.12% by mass of superplasticizer was used for the 20% RCF replacement mortar samples and 0.24% for the 30% RCF replacement mortar samples. 800 °C treated RCF has the highest water demand, with the same w/c ratio and the same superplasticizer dosage; the flow table spread value of the 800 °C treated mortar samples was the lowest when comparing to the corresponding untreated RCF and 500 °C treated RCF. The reasons for the higher water demand of the RCF can be explained by the higher specific surface of the hydrated cement than the unhydrated cement (Shui et al., 2009). As for the 800 °C treated RCF, the CaO reacts with water quickly, moreover, the dehydrated C-S-H and some other dehydrated phases such as ettringite are recovered to their original structures with a fast speed (Shui et al., 2009); thus leading to a quick setting of the mortar samples.

The obtained mortar sample strengths are depicted in Figure 11 and Figure 12.

It is observed from Figure 11 (left) that, with the increasing cement replacement ratio, the 7 days flexural strength of mortar samples decreases. The reference mortar has the highest 7 days flexural strength of 6.18 MPa. At 10% replacement ratio, 500 °C treated RCF mortar has the lowest flexural strength among all; fly ash, untreated RCF and 800 °C treated RCF obtained very good flexural strength when comparing to the reference mortar. At 20% replacement ratio, 800 °C treated RCF obtained the highest flexural strength among all the substituting materials, which is 5.44 MPa. From 10% to 20% replacement ratio, the 800 °C treated RCF achieved almost the same flexural strength. 30% of replacement ratio the flexural strength for all the materials significantly.

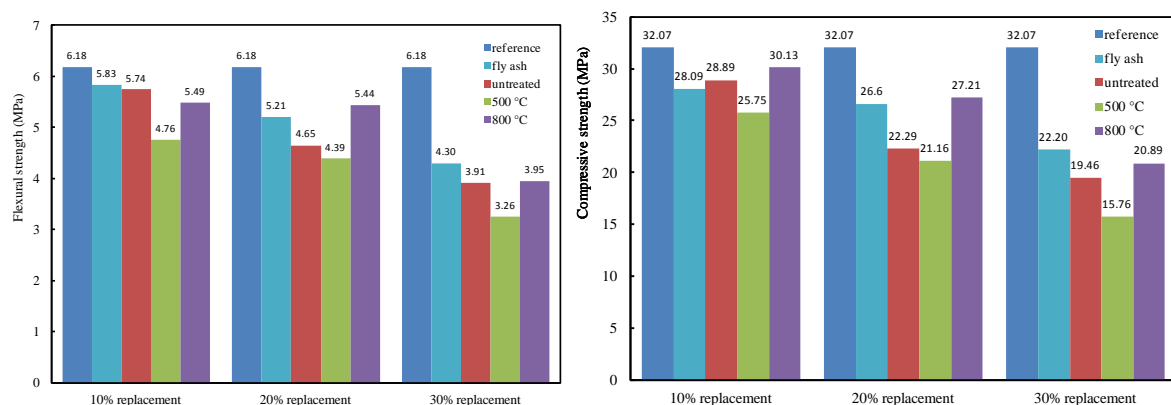


Figure 11. 7 days flexural strength (left) and compressive (right) strength of RCFs at different replacement ratios.

As can be seen from Figure 11 (right), the 7 days compressive strength of all the substitution materials decreases with the increased replacement ratio. 500 °C treated RCF has the lowest 7 days compressive strength in all the replacement ratios. At 10% replacement ratio, 800 °C treated RCF has a higher strength than the rest substitution materials; however, it is still 6% lower than the reference. At 20% replacement ratio, 800 °C treated RCF is still performing better than the other material but it is 15.2% lower than the reference mortar. It should be

noted that the compressive strength decreases with less than the replacement ratio, which indicates that the RCF contributes to the development of strength. At 30% replacement ratio, all the substitute material decreased the compressive strength for more than 30% comparing to the reference; fly ash, in this case, has the highest 7 days compressive strength of 22.2 MPa, is 30.8% lower than the reference.

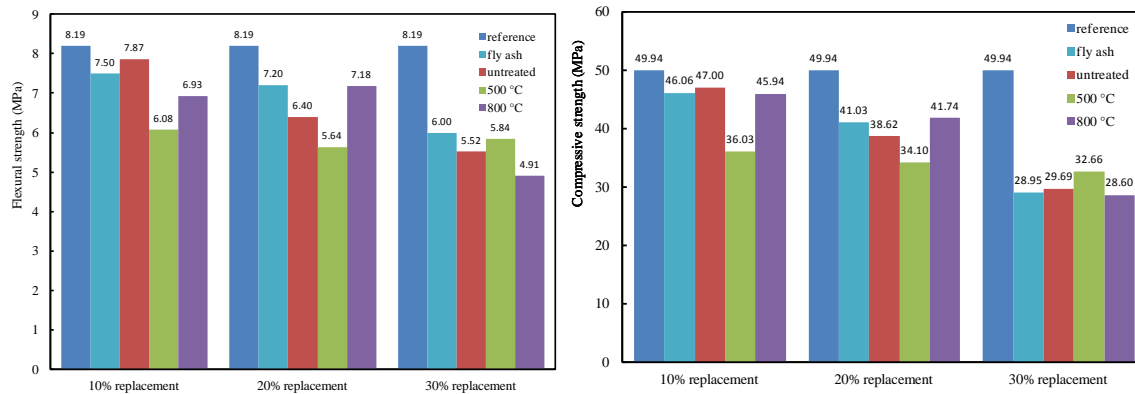


Figure 12. 28 days flexural strength (left) and compressive strength (right) of RCFs at different replacement ratios.

As can be seen from Figure 12 (left), the increased replacement ratio is no longer decreasing the 28 days flexural strength of the mortar samples. For instance, 500 °C treated RCF at 30% replacement ratio, has the flexural strength of 5.84 MPa, which is higher than the 20% replacement one with 5.64 MPa. 800 °C treated RCF has the 28 days flexural strength of 7.18 MPa at 30% of replacement ratio, which is higher than 6.93 for the 10% replacement sample. Untreated RCF at 10% of replacement ratio is better than any other substitution materials with the flexural strength of 7.87 MPa which is only 3.9% lower than the reference mortar. At 20% of replacement ratio, fly ash and 800 °C treated RCF are both higher than 80% of the reference strength. This means that fly ash and 800 °C treated RCF can contribute to the strength of the mortar samples.

At 10% replacement ratio, fly ash, untreated RCF and 800 °C treated RCF showed good mechanical performances; the 28 days compressive strengths were all higher than 90% of the reference mortar and were enough to fulfill the specifications of the strength class 42.5 as required by the characteristic strength of EN 197-1. Untreated RCF, with the 28 days compressive strength of 47 MPa for 10% replacement ratio is the best one in all the replacement materials. At 20% replacement ratio, fly ash and 800 °C treated RCF performed better than the 80% strength of the reference mortar, which means they can both contribute to the mechanical strength of the mortar samples. 500 °C treated RCF, on the other hand, is the worst at the 10% and 20% replacement ratios, however is the best for the 30% replacement ratio. 800 °C treated RCF has the equivalent 28 days strength as the fly ash in all the tested replacement ratios.

The results can be explained as: PKVA fly ash, which has a low lime content, needs calcium hydroxide to accelerate the pozzolanic activity. It also can improve the consistence and cohesiveness of the fresh mortar paste. However, at 30% of replacement, calcium hydroxide, the cement hydration product, is not enough to activate the fly ash, reduced the 28 days compressive strength by 42%. RCF, no matter untreated or thermally treated needs more

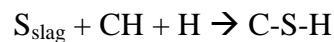


water than cement. At 10% replacement, RCF without thermal treatment acts mainly as filler material, which can act as nucleation sites for the cement hydration products. Moreover, calcium carbonate was found in RCF, which has some reaction with the aluminate phases in the cement (Illston & Domone, 2001). At 20% replacement, the high water absorption value of the untreated RCF has caused a deleterious effect on the hydration process. 500 °C treated RCF with dehydrated cement paste and CaO formed in it, increases the water absorption value. Although dehydrated cement paste can recover the original hydration products (Shui et al., 2008), it is speculated that the influence of the water demand is the dominant effect over that of the rehydration. 800 °C treated RCF, with increased water demand, however, has more phases involved in the rehydration process, can be beneficial for the compressive strength development.

Actually, 1100 °C treated RCF was also used to replace 10% of the cement, however, the resulted 28 days compressive strength was only 36.86 MPa. This result was not encouraging enough to continue the experiment to a higher replacement ratio. This result was also in agreement with the result of Shui (2009) that the thermal treatment temperature higher than 800 °C will decrease the rehydrated cement paste strength. This can be explained as at the temperature of 1100 °C, the evaporation of chemically bound water destroyed the structure of the hydration products. When meet water again, the treated phases can no longer recover to the original hydration products.

## V.2. Slag cement replacement test

In the Netherlands, more than 50% of the cement delivered to the market is CEM III, which has a relatively large amount of slag and small amount of cement clinker (Wei, 2006). The theory behind the pozzolanic reaction is the formation of C-S-H gel from glassy SiO<sub>2</sub> and Ca(OH)<sub>2</sub> (Illston & Domone, 2001).



Slag has a certain level of self cementing ability because of the existence of lime and glassy SiO<sub>2</sub> in it. Cement is used to further activate the slag. 70% of slag mixed with 30% of cement was used as the reference. RCF, untreated and thermally treated were used to replace 33% of the cement in the slag cement blend. The water/binder ratio was kept at 0.5. The mix proportioning of the tested mortars is given in Table 5.

Table 5. Mix proportioning of the tested mortars for slag activation by RCF.

Material	Reference (g)	Untreated RCF (g)	500 °C treated RCF (g)	800 °C treated RCF (g)
Norm sand	1350	1350	1350	1350
CEM I 42.5 N	135	90	90	90
Slag	315	315	315	315
RCF	0	45	45	45
Water	225	225	225	225



The 7 days and 28 days compressive strengths of the tested mortar samples are depicted in Figure 13.

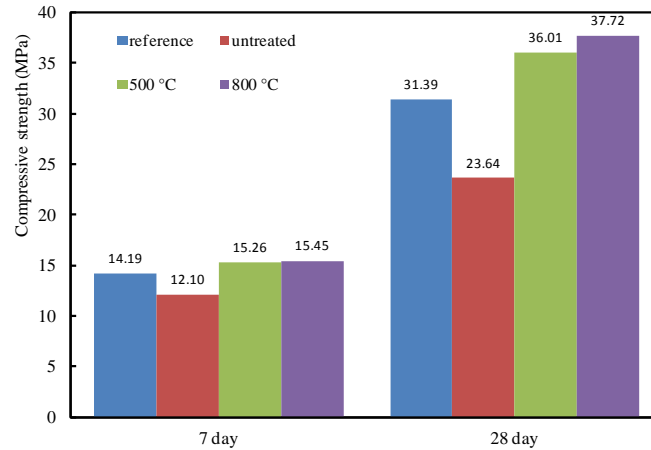


Figure 13. 7 days and 28 days compressive strength of slag blended cement mortars.

It can be seen from Figure 13 that the untreated RCF mortar has the lowest 7 days and 28 days compressive strengths. 500 °C treated RCF increases the 7 days compressive strength by 7.5% and 28 days compressive strength by 14.7%. 800 °C treated RCF, has even better performance in slag activation; the 7 days compressive strength increases by 8.8% and the 28 days compressive strength increases by 20.1%.

Shui (2011) used dehydrated cement paste to activate fly ash. It is proven in this research that thermally treated RCF can also be used to activate slag. Untreated RCF, without lime in it, has a detrimental effect to the mortar strength. 500 °C and 800 °C treated RCF, with the free lime in them, have an activation effect of the slag. CH is also a hydration product of cement; however, it takes some time to form the hydration products. 500 °C and 800 °C treated RCF, with free lime in them, can create the alkali environment for the pozzolanic reaction at the beginning of the reaction. This leads to the higher compressive strength than the reference mortar samples. Moreover, as can be seen in the source concrete recipe, about 1.7% of limestone powder was added in. Which means more free lime was produced through the 800 °C treated RCF.

### V.3. Combining thermally treated RCFs with fly ash

Dehydrated cement paste was found to have the activation effect on fly ash by Shui (2011). In this research, 800 °C treated RCF was combined with PKVA fly ash together to replace cement in the standard mortar sample. It was observed that 800 °C treated RCF could decrease the fresh mortar consistence. When it was used to replace 20% of cement, superplasticizer was used to achieve a good fresh mortar property. Fly ash, on contrary, has the property of increasing the fresh mortar property when being used concrete (Illston & Domone, 2001). Moreover, the free lime existing in 800 °C treated RCF is believed to activate the pozzolanic activity of PKVA fly ash. 10% 800 °C treated RCF+10% PKVA fly ash were used together to replace 20% of cement in the standard mortar.

The fresh mortar consistence was tested by flow table test, the spread of the 10% 800 °C treated RCF+10% PKVA fly ash mortar sample was 141 mm comparing to the spread value

139 mm of the reference sample. It can be concluded that 10% of PKVA fly ash can fully compensate the fresh mortar consistence loss caused by 10% of 800 °C treated RCF. By using 800 °C treated RCF along with PKVA fly ash can increase the cement replacement ratio without losing the fresh mortar property.

Table 6. Mix proportioning of the tested mortars for combining RCF together with fly ash.

Material (g)	Reference	RCF + fly ash
Norm sand	1350	1350
CEM I 42.5 N	450	360
PKVA fly ash	0	45
800 °C treated RCF	0	45
Water	225	225

Mortar samples by replacing cement by 20% of 800 °C treated RCF and by 20% of PKVA fly ash are also used for comparison. The 7 days and 28 days flexural and compressive strength are presented in Figure 14.

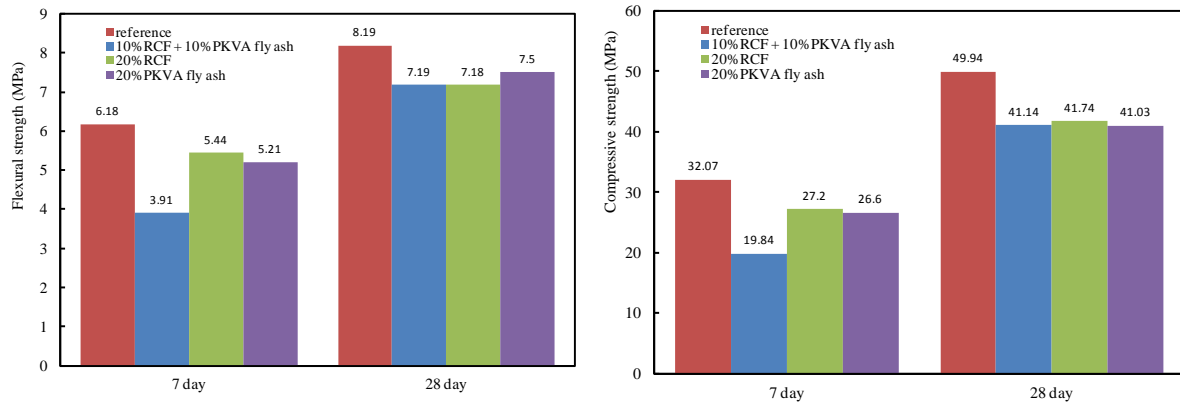


Figure 14. 7 days and 28 days flexural strength (left) and compressive strength (right) of the reference, 10% 800 °C treated RCF+10% PKVA fly, 20% 800 °C treated RCF and 20% PKVA fly ash replacement mortars.

It can be seen from Figure 14 (left) that the 7 days flexural strength of the RCF + fly ash sample is the lowest one among all the samples. The 7 days flexural strength is reduced by 36.7% when comparing to the reference. However, the RCF + fly ash sample obtained very encouraging 28 days flexural strength of 7.19 MPa. This value is only 12.2% lower than the reference and is equal to the 20% RCF sample.

It is illustrated in Figure 14 (right) that the 7 days compressive strength of the RCF + fly ash sample is 38.1% lower than the reference sample. It is also much lower than the 20% RCF and 20% PKVA fly ash sample. The 28 days compressive strength of the RCF + fly ash

sample is 41.14 MPa which is 17.6% lower than the reference mortar. All of the three 20% cement replacement samples showed almost identical 28 days compressive strength results.

Conclusions can be made based on the experiment result as that: PKVA fly ash is able to compensate the fresh mortar consistence loss caused by 800 °C treated RCF. Using 10% 800 °C treated RCF + 10% PKVA fly ash together can lead to a large decrease of the mortar sample 7 days flexural and compressive strength. However, the 28 days flexural and compressive strength were good enough for encouraging the use of both the materials together. The mechanical strength of the mortar sample increased mostly after 7 days, it is believed that using the 800 °C treated RCF + PKVA fly ash together has certain retarding effect to the mortar sample mechanical strength development.

## VI. Recycled concrete aggregates replacement tests

In this part of the research, recycled concrete sand (RCS) was used to replace 100% of Norm sand. Norm sand was used to make the reference mortar sample.

At the beginning, two bags of Norm sand were sieved; the average values of the sieved results are presented in Table 7. Based on the mass of sand that was retained on each sieve, the same mass of RCS was used to constitute RCS sand. The net weight of each bag of the Norm sand was 1350 grams, there were about 5 grams of losses during sieving; the amount of RCS was modified to obtain the same total weight as a bag of Norm sand before sieving.

Table 7. Sieving Norm sand and the mass of RCS used

Particle size	Norm sand (g)	RCS (g)
<75 µm	2.9	3
75-150 µm	120.8	121
150-500 µm	316.2	318
0.5-1 mm	428.4	430
1-1.4 mm	250.9	251
1.4-2 mm	225.9	227
<b>Total</b>	<b>1345.1</b>	<b>1350</b>

Because of the high water absorption value of RCS, about 1% of superplasticizer (SP) was used in the RCS sample in order to increase the workability. The dosage of 1% here is the ratio of SP to cement by mass.

It's can be seen from Figure 15 (left) that by replacing Norm sand by RCS, the 28 days flexural strength increased by 13.7%, 7 day flexural strength increased by 33.1%, 3 day flexural strength increased by 45.3%.

As can be seen in Figure 15 (right), the RCS samples show a slightly higher 28 day compressive strength than the Norm sand sample. There is a 65.6% increase for 3 days compressive strength and 40% increase for 7 days compressive strength.

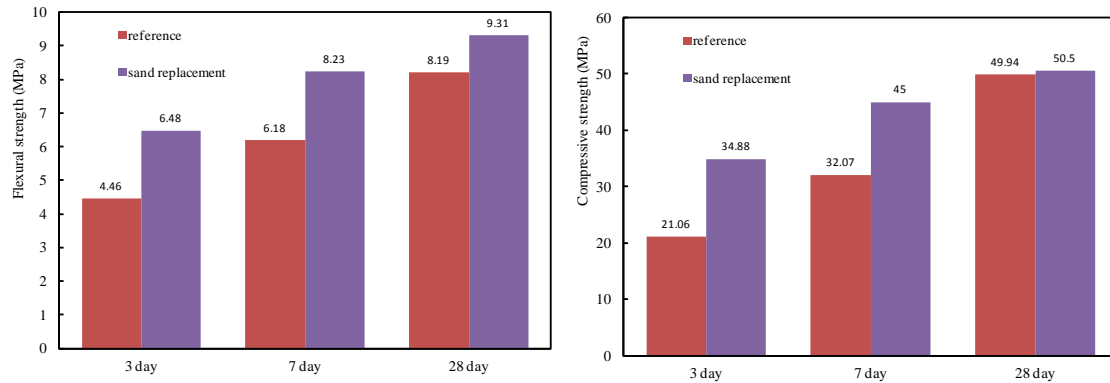


Figure 15. Flexural (left) and compressive strength (right) of mortar sand replacement

Therefore, it can be concluded that RCS has a higher water absorption value than Norm sand. In order to use RCS in new concrete, superplasticizer was used to achieve the required workability. RCS can increase both the flexural strength and compressive strength of the mortars. RCS contributes especially to the early strength of the test samples.

## Summary and conclusions

The main objective of this research is to use recycled concrete fines to replace part of the cement in new concrete production through a thermal treatment method. Cement is the most energy consumption component of concrete, with high CO<sub>2</sub> emission during its manufacturing. If a certain amount of cement can be replaced by recycled concrete fines, it will increase the recycled material application level and thus help environment protection and natural resources preservation. Based on the experimental research, the conclusions and some discussions will be presented in the following part.

In this research, laboratory made concrete was used to mimic the concrete recycling process. A specially designed smart crusher prototype was used to separate cement paste from concrete aggregates. The obtained recycled concrete aggregates were collected and separated into different fractions based on the particle sizes. A concrete recipe was designed and optimized, 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 laboratory-scale 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. All particle size fractions of the recycled concrete aggregates (RCA) were studied in this research. It was found that the smaller particle size the RCAs have, the less  $\alpha$ -quartz content there is. It is also found that the density of the RCA has a correlation with the  $\alpha$ -quartz content: low density means a relatively low  $\alpha$ -quartz content.

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 DTA 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 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  $\alpha$ -SiO<sub>2</sub> than the ones from the RCA I series.*** The SC 1 fines contained a maximum of 27%  $\alpha$ -SiO<sub>2</sub> in the 0-63  $\mu$  fraction and under 42% in the 63-125  $\mu$ m, as opposed to approx. 50% in the finest fraction obtained from RCA I. A modified version of the SC1 and a more thorough crushing method led to cleaner aggregates (see Figure 8 and explanation).

As for the thermal treatment, it is preferred to have the RCF that are small in size. Particles under 150  $\mu$ m were used as the material for thermal treatment. The thermal treatment can dehydrate the cement paste portion within the RCF, which can liberate the cementitious ability of RCF. When the thermal treatment temperature was selected as 500 °C, the major phase changes were the dehydration of the C-S-H gel, ettringite and the dissociation of most part of the portlandite. When the thermal treatment temperature was increased to 800 °C, calcite will also decompose to lime and carbon dioxide.  $\alpha$ -quartz has the phase transformation at the temperature of about 573 °C and is recovered to  $\alpha$ -quartz again when cooled down to room temperature. A fast cooling down could prevent this transformation, thus leading to preserving the silica in its reactive  $\beta$  form; this possibility is still under investigation .

Mortar tests were made on slag-cement standard mortars in order to assess the suitability of recycled concrete fines from the SC 1 as cement replacement. ***The results have shown that the recycled concrete fines have a contribution to the strength development of the mortars.*** Especially for the early strength (3 days), no loss of strength was observed. For the 28-days strength, the loss of mechanical properties was lower than it would have been expected for inert replacements, which shows that the recycled concrete fines bring their contribution to the strength development of the samples.

***It was demonstrated in this study that untreated RCF and 800 °C treated RCF can be used in mortar samples up to 20% replacement ratio without causing large detrimental effects on the mechanical properties in hardened state.*** At 10% replacement ratio of cement, there was no evident decrease of the mortar spread. The CEM I 42.5 N cement with 10% replaced by untreated RCF or 800 °C treated RCF can still be categorized as strength class 42.5 according to the European standard of EN 197-1. The performance of 800 °C treated RCF was also compared with class F fly ash. It was found that 800 °C treated RCF had equivalent mechanical performances as fly ash. The only difference is that 800 °C treated RCF decreases the mortar sample fresh properties, therefore superplasticizer was used to obtain the same spread value. 500 °C treated RCF was found not be suitable to use as cement replacement material because of the detrimental effect on the mortar strength. All the cement substitution materials showed a negative effect at 30% replacement ratio because of the water absorption value and the dilution effect to the cement.

***Thermally treated RCFs (both 500 °C treated RCF and 800 °C treated RCF) showed an activation effect on slag. It was found that 33% replacement of the CEM I 42.5 by 500 °C treated RCF and 800 °C treated RCF (Table 5) can increase the 28 days compressive strength of slag and cement-RCF blend by 14.7% and 20.1% respectively . This can be explained by the pozzolanic effect caused by the free lime in the thermally treated RCF and the quick rehydration of the dehydrated cement paste. Moreover, the used RCF still contained ~ 30%  $\alpha$ -SiO<sub>2</sub>; a reduction of this silica-content could lead to increased performance of the RCF.***

***Recycled concrete sand was tested to replace 100% of the Norm sand in the standard mortar sample. The mechanical performance of the RCS test was very encouraging. The RCS mortar samples obtained higher strength than the reference samples, especially for the early strength.*** The 3 days, 7 days and 28 days flexural strength increased by 45.3%, 33.2% and 13.7% respectively. The 3 days and 7 days compressive strength increased by 65.6% and 40.3%, respectively. However, the 28 days compressive strength increased only by 1.1%.

Based on the research presented in the study, there are several things necessary to be discussed:

- The laboratory recycled concrete aggregates have a much better quality comparing to the field recycled concrete aggregates which usually have contaminants blended in them. The contaminants, usually brick, glass, plastic or organic materials, can cause unexpected side effects to the cement quality when they are used to replace part of the cement in concrete production.
- A compromise on the RCF material particle size was made because of the amount of the RCF that can be obtained in the laboratory. As can be seen in this study, the smaller sized RCF has significantly lower amounts of  $\alpha$ -quartz, which is considered as inert. It is speculated that better results can be obtained if particles under 63  $\mu$ m can be used instead of the 150  $\mu$ m RCF, because RCF with small particles sizes also have more contact surface with water during hydration.
- RCF which has similar chemical compositions as cement, can possibly be used as part of the raw material for cement production. However, this is not easy to realize on laboratory scale.

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