

MASTER

Thermal treatment of recycled concrete fines

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Award date:
2012

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Thermal Treatment of Recycled Concrete Fines

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Document information:

Course number: Master project Building Services 7YY40
Date: 14 June 2012

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“Waste equals food”

—William McDonough & Michael Braungart,

Cradle to Cradle--Remaking the Way We Make Things

Preface

I came to Eindhoven University of Technology (TU/e) in August 2010. It's been about two years that I live here in The Netherlands. I really enjoy the peaceful life here. I feel so grateful to TU/e for offering me the TSP scholarship which makes it possible for me to study here.

This thesis is the results of one year's work for my graduation project of the master program "Building Services" in the department of Built Environment of TU/e. With the intensive education in this program, I started to get interested in the field of sustainable building. The sustainable buildings have to be energy saving during their life spans and, of course, consume less raw materials from our planet. That's why I chose to do my graduation project in the topic of concrete recycling.

I want to express my gratitude to Dipl. Eng. Miruna Florea for your hand to hand guidance for leading me to the field of sustainable building materials. You've been an encouraging and inspiring supervisor to work with. I want to thank Professor Jos Brouwers for giving me this project to work on and your help with my thesis. Dr. Qingliang Yu has given me a lot of invaluable suggestions on my research, career and life, thanks a lot! I would like to thank Mr. Koos Jacobus Schenk, thanks for initiating this project and thanks for your help with your nice smart crusher. Thanks to Theo Pouw Group for the financial support of this project.

I also would like to thank my dear colleagues in the sustainable building material group: Przemek Spiesz, George Quercia, Alberto Lázaro, Rui Yu, Pei Tang, Azee Taher and Stepan Lorencik. Thanks for all your help with my experiments and the great time that we spent together on the football field. Thanks to you Guillaume Doudart de la Grée, it's been great to have your companion during the whole research period. Wish you a big success in your PhD study! Thanks to Mr. Peter Cappon for your technical support in the laboratory! Thanks to Dipl. Eng. Daniel Florea for helping me with the SEM measurement. Furthermore, I would like to thank my fellow friends in the study association of Mollier, you made my life colorful in Eindhoven.

Finally, and definitely I would like to thank you Xin Zhang, you are the most important one in my life! My parents and my sister, without your support, this thesis would not have existed. Thanks to you my uncle Xinlin Zuo, your support gave me the strength and confidence to face the challenges in my life!

Ning Zuokui

June 2012, Eindhoven

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1 Introduction

As described by William McDonough (2002) in the cradle to cradle concept, the materials circulating in the world can be divided into two circles. The first circle is the biosphere, which has been stably existing on earth for millions of years. The second circle is the industrial circle. It altered the natural equilibrium of materials on the planet. It is wished that the materials taken from the Earth by humans can safely be returned to nature after their service lives or can become nutrients for new products. In other words, a closed-loop material circle is most desirable for all the materials circulating in the industrial circle. In this ideal state, the so called waste is the food for new products. However, in practice, the cradle to cradle concept is still far from being realized. Most of the industrialized materials are still being downcycled or even landfilled. Construction and demolition, for instance, produce large amount of waste materials that can hardly be fully recycled. This thesis will be focused on the utilization of recycled concrete fines.

1.1 Problem description

1.1.1 How much C&D waste is produced and recycled every year?

Concrete is the most consumed manmade material worldwide. According to the statistics from The European Cement Association (CEMBUREAU, 2011), 3.3 billion tons of cement were produced in 2010 worldwide. It is estimated that cement production figures equate to about 8% to 12% of concrete production, so roughly 28 to 41 billion tons of concrete were produced in 2010 worldwide. New cement and concrete are mainly produced in developing and emerging economies like China and India. Figure 1.1 shows the regional breakdown of cement production.

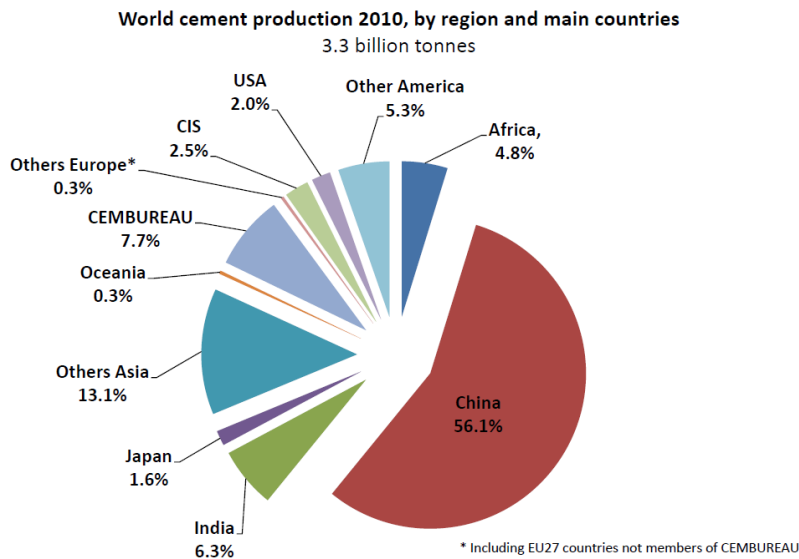


Figure 1.1 Regional breakdown of cement production 2010 (CEMBUREAU, 2011)

However, worldwide statistics of concrete and demolition waste generation and recovery are not available, because there are no standardized definition or measurement methods. For instance, some countries take

excavated soil into consideration while others do not. World Business Council for Sustainable Development has made a table (CSI, 2011) for C&D waste generation and recovery of some countries.

Table 1.1 C&D waste generation and recovery from some countries and regions (CSI, 2011)

Country	Total C&DW (Mt)	Total Recovery(Mt)	%C&DW Recovery
Australia	14	8	57
Belgium	14	12	86
Canada	N/A	8 (recycled concrete)	N/A
Czech Republic	9 (incl. 3 of concrete)	1 (recycled concrete)	45 (concrete)
England	90	46	50 - 90
France	309	195	63
Germany	201	179	89
Ireland	17	13	80
Japan	77	62	80
Netherlands	26	25	95
Norway	N/A	N/A	50 - 70
Spain	39	4	10
Switzerland	7 (incl. 2 of concrete)	2	Near 100
Taiwan	63	58	91
US	317 (incl. 155 of concrete)	127 (recycled concrete)	82

These large amounts of C&D waste, if not treated properly, become trash that has to be landfilled as normal rubbish. If they can be recycled and treated according to their characteristics, economical and environmental benefits can be obtained. High levels of recycling are achieved in countries like Netherlands, Japan, Belgium and Germany. Concrete recycling can become a promising industry in countries like China and India in the coming years.

1.1.2 Benefits and problems of construction and demolition waste recycling

Concrete and demolition waste recycling can bring many benefits for the environment and economy. One of the benefits is that it reduces land use for trash landfill. To take Netherlands as an example, landfill of construction waste is banned all over the country. C&D waste recycling plants solve the problem by producing materials that are qualified as new building materials. C&D waste recycling basically makes it one step forward in sustainable development.

Another benefit is that C&D waste recycling reduces the use of new virgin aggregates because the recycled concrete aggregate can be used in road base, sub base or in the production of new concrete. New virgin aggregates are from river sand or rocky mountains. The exploitation of new concrete aggregates destroys the environmental system and the original landscape. In China, due to the recent construction boom, it is very hard to get natural river sand in some regions. Mechanically made aggregates have to be crushed from stones. At the same time, transportation cost will be reduced if C&D waste can be reused in new constructions.

In the recent years, great attention has been paid to green house effect gases such as CO₂. The production of cement has a very significant contribution of CO₂ emission. It is reported that the cement industry alone is estimated to be responsible for about 7% of all CO₂ generated (Meyer, 2009). Along with CO₂ emission, energy consumption and water consumption also cause considerable problems to the planet. However, CO₂ reduction is still a challenging problem for C&D waste recycling, because CO₂ is mostly generated during the cement production stage. By using recycled concrete aggregates in new constructions, CO₂ can also be reduced by decreasing the transportation of virgin aggregates from remote areas.

In Japan and some states of US, the construction industry uses recycled concrete aggregates (RCA) in substituting a proportion of natural aggregates (Meyer, 2009; CSI, 2011). While in Europe, most of the recycled C&D debris is downcycled and used for road base or sub-base material (Hansen and Lauritzen, 2004).

Generally speaking, recycled concrete aggregates (RCA) have a lower density and higher water absorption than the original aggregates used, because of the cement mortar that remains attached to the aggregate particles (Hansen, 1992). 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.

Another problem of RCA is the variety of contaminants such as plaster, oil, wood, gypsum, asphalt and rubber that are mixed during the demolition process. Even a small amount of contaminants can degrade the strength and durability of the concrete made with them (Meyer, 2009). RCA contamination control has to be started at the beginning of each demolition project.

It is found that adding RCA in new concrete will decrease the compressive strength (Hansen, 1992). Adding less than 30% of coarse RCA in new concrete will not reduce compressive strength significantly. Because fine RCA, which is smaller than 1 mm is thought to cause a higher strength loss, they are mostly not being used in new concrete production. The use of RCA in new concrete also reduces the elastic modulus, increases creep and shrinkage deformation. Recycled aggregate concrete (RAC) has a higher permeability which decreases its durability (Meyer, 2009). In summary, recycled aggregate concrete has a lower quality than concrete made with virgin concrete aggregate.

1.1.3 Concrete recycling process

At the demolition site, mobile sorters and crushers are used to pre sort and treat the demolition debris. Strict quality control starts at the site, in order to reduce various types of contaminants. Wood, gypsum, plastics and rubber etc., will degrade the RCA quality in the future; the best way is not to mix them in the materials that go to a concrete recycling plant.

The main steps of the concrete recycling process are crushing, sieving and removal of contaminants. A typical crusher system for concrete recycling is presented in Figure 1.2.

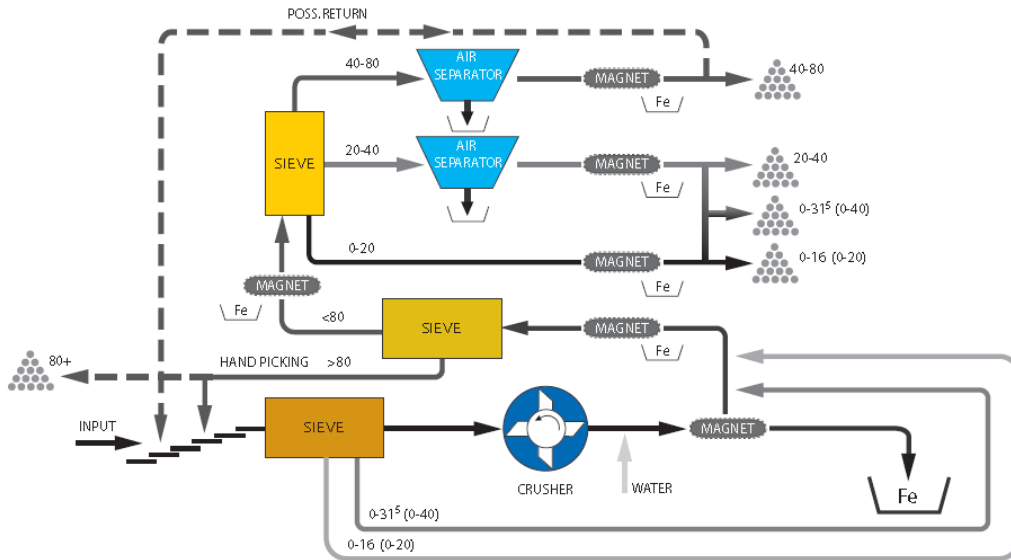


Figure 1.2 A representative crusher system for concrete recycling (Van Bentum Recycling Centrale, 2011).

As shown in Figure 1.2, at the recycling plant, large pieces of debris from the demolition sites are typically reduced to 0.4-0.7 m maximum size (Hansen, 1992). Large pieces of steel, wood, plastics etc. are removed by hand. All the debris first goes to the vibrating screen. Resulting large pieces go to the impact crusher where the material is reduced to smaller pieces. The electrical magnet is used to remove metal particles, such as reinforced steel. Then, the reduced particles go to a sorting unit where they are separated into different sizes. An air separator may be used for removing light materials, magnet is used once again to collect the remaining steel in the crushed material. The big particles that can not go through the screens are sent back to the crusher again until they are finally crushed and sieved to different particle sizes.

1.1.4 Recycled concrete fines

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 hardened cement paste and α -quartz originated from broken aggregates. 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.

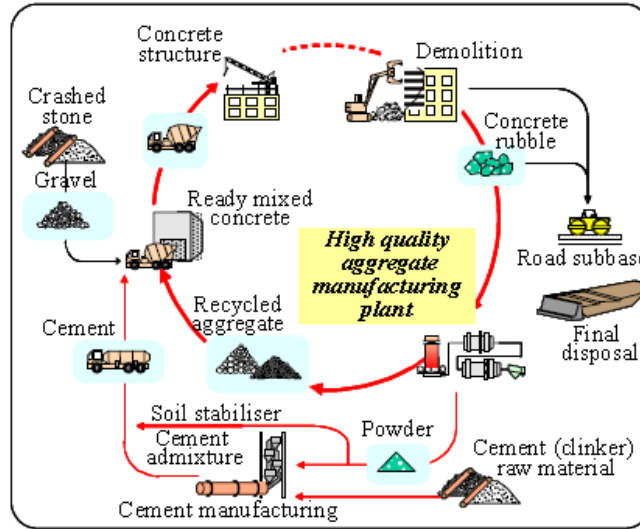


Figure 1.3 The vision of total concrete recycling proposed by Shima (2005)

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 a good activation effect (Shui et al., 2011). The principle difference between RCF and pure cement paste is the existence of α -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.

1.2 Objectives and research questions

The main objective of this research is to use thermal treatment method to activate RCF and use the treated RCF as binder material for new concrete production.

RCF has different α -quartz content depends on the particle sizes. The α -quartz part of RCF is considered as inert during the thermal treatment process. Only the cement paste part is considered as the desired material for thermal treatment. Of course, it is wanted to have the RCF that is rich in cement paste. It is found that the dehydration temperature has a very big influence on the cementitious properties of dehydrated cement paste (Shui et al., 2009). Four research questions are formulated: What are the physical and chemical properties of RCF? How to select the RCF which is rich in cement paste? What is the optimum thermal treatment temperature for the selected RCF? How to apply the thermally treated RCF as binder material?

1.3 Outline of the thesis

This thesis aims to use the margin material which is produced during the concrete recycling process. If RCF can be applied successfully, the material loop of concrete can be closed one step further. The knowledge of cement chemistry and the fresh and hardened properties are especially important for this research. Laboratory work is also important for testing the suggested approach and to explore the theories behind the thermal treatment method.

Chapter 2 of this thesis is the literature study which was carried out at the beginning of this research. In this part, books and articles were extensively studied and the literature summaries are presented. This part is divided into several topics: Crushing methods used in concrete recycling industry; Cement chemistry; Cement substitution materials; Dehydration of hardened cement paste under high temperature; Fresh and hardened properties of concrete incorporating recycled concrete aggregates; Concrete recycling and green building certificates.

Chapter 3 of this thesis present the theories of the laboratory techniques that are used for this research. With the help of those techniques, the physical, chemical and mineralogical properties of RCF can be explored. Standardized methods for testing the fresh and hardened properties of mortar samples are also presented in this chapter. Another important topic for this research is the smart crushing technique which is also explained in detail in this chapter.

Chapter 4 is the experiment part of this research. The experiment process and results are presented in detail. The purpose of this chapter is to make this research repeatable by other researchers. This chapter follows a logical order, starting from the coarse concrete preparation followed by the RCF analyzing until the application of thermally treated RCF.

Chapter 5 is the conclusion of this thesis. Based on the experiment result, conclusions, discussions and the future work are presented. The four research questions mentioned in the Introduction part are answered.

2 Literature study

2.1 Crushing methods

Crushing in the concrete recycling industry may be defined as the process or the group of operations that reduce large concrete lumps to fragments (Hansen, 1992). Although, in general, the object of crushing is size reduction only, for concrete recycling, it is coupled with a requirement for the better separation of mortar from aggregates. The recycled aggregates with less mortar attached to them are considered better since a lower water absorption value is achieved. Normally, two types of crushers are required in a concrete recycling plant; namely the primary crusher and secondary crusher. The primary crusher is used to crush the old concrete to the largest size that will fit the secondary crusher. Hansen (1992) concluded that the properties of recycled concrete aggregates are always improved by secondary crushing.

A number of types of crushers are used in concrete crushing, such as jaw crusher, cone crusher, hammer mills, and the impact crusher. The crushing action in all crushing machines results from stresses that are applied to the particles to be crushed by a moving part in the machine, working against a stationary part or against another moving part (Gaudin, 1939). The working principle is that: the stresses lead to strains within the particles, resulting in fracturing whenever they exceed the elastic limit of the material. In describing the crushing operation, the ratio of the maximum size of the particles in the feed and in the product is used. It is called the reduction ratio or crushing ratio. In the following part, jaw crushers, cone crushers and impact crushers will be described.

2.1.1 Jaw crusher

The main characteristic that distinguishes a jaw crusher is that it consists of two flat crushing faces called jaws. One jaw is movable which moves alternately toward the stationary jaw while the stationary one is usually mounted rigidly in the crusher frame. A jaw crusher is mainly comprised of frame, flywheel, movable jaw, fixed jaw, toggle plate, set adjustment, main bearing and motor. An image of a jaw crusher is presented in Figure 2.1. The toggle plate is mainly used for overpressure protection.

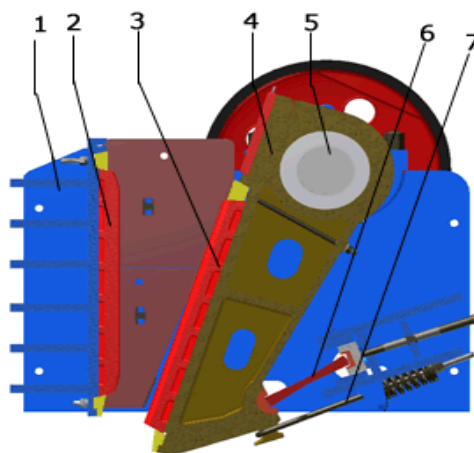


Figure 2.1 Sectional view of a jaw crusher (Stonecrusher.org, 2011)(1. Frame; 2. Fixed Jaw; 3. Moving Jaw Plate; 4. Move Jaw; 5. Eccentric Shaft; 6. Toggle Plate; 7. Adjusting Toggle Seat)

Because jaw crushers have a relatively large width of receiving opening, they are intended for the use as primary crushers. The length of the receiving opening is generally somewhat greater than the width (Gaudin, 1939). All jaw crushers have an adjustable discharge opening so that they can produce a final product with a size depending on the adjustable limit of the machine. The capacity of the jaw crusher is usually large, for instance, 650 tons of concrete per hour (Jaw crusher model PE 1200x1500, Zhengzhou Great Wall Industry machinery CO., LTD). Therefore, the energy consumption is also very high. The energy consumption depends upon the following factors: size of feed, properties of feeding material, size of product, capacity of machine and percentage of idling time (Gaudin, 1939). Wear of the jaw plates is the main source of expenses for a jaw crusher; they need to be replaced from time to time.

2.1.2 Cone crusher

Cone crushers are sometimes called gyratory cone crushers. Cone crushers crush concrete between two conical shells that are called the mantle and the concave liners, respectively. The outer shell is stationary and the inner shell is made to rotate, thus alternately receding from and approaching all the points on the periphery of the outer shell. The cone crusher is comprised of mantle, concave liner, main shaft, fly wheel, bearing and motor. Figure 2.2 shows the working principle of a cone crusher.

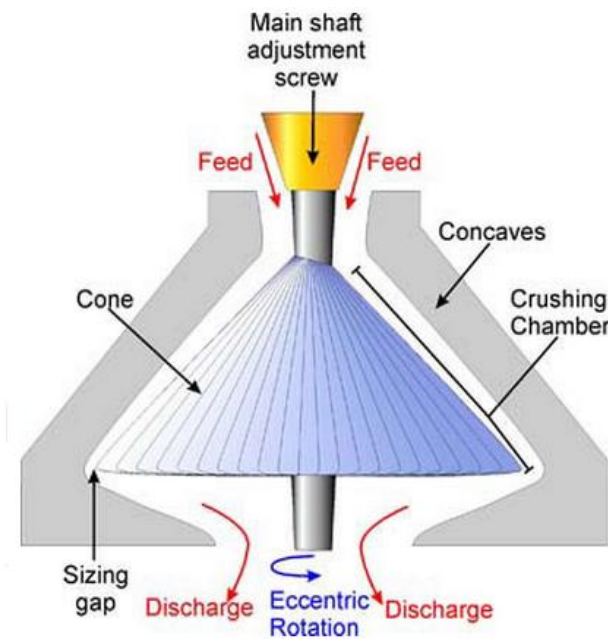


Figure 2.2 Principle of a cone crusher (Planning Minerals, 2011)

Cone crushers can be used in primary crushing but are more often used for the secondary or tertiary crushing. The capacity of cone crushers is much greater than that of jaw crushers handling the same size of feed (Gaudin, 1939). This is because that cone crushers work continuously while jaw crushers work intermittently. In some factors like crushing ratio, power consumption at equivalent capacity, cone crushers are equal to jaw crushers. It is suggested that when the quantity to be crushed is sufficiently small to be handled by one jaw crusher, it is more economical to use the jaw crusher. If the quantity to be crushed can make the cone crusher work at its maximum capacity, then the cone crusher is more

preferable. Some other factors may also need to be taken into consideration when selecting crushers, for instance, the size of the feed opening and the product size distribution.

2.1.3 Impact crusher

Impact crushers are mainly used in secondary crushing. An impact crusher is mainly comprised of rotor, board hammer, impact plate and of course, motor; see Figure 2.3. The principle of impact crusher is that when the materials are added from the feed opening, the rotor drives them to the impact plate with a very high speed. The large pieces are then broken into small pieces. When the small particles fall down to the rotor, they are thrown to the impact plate once again. The crushed materials then fall out of the crushing chamber from the discharge opening.

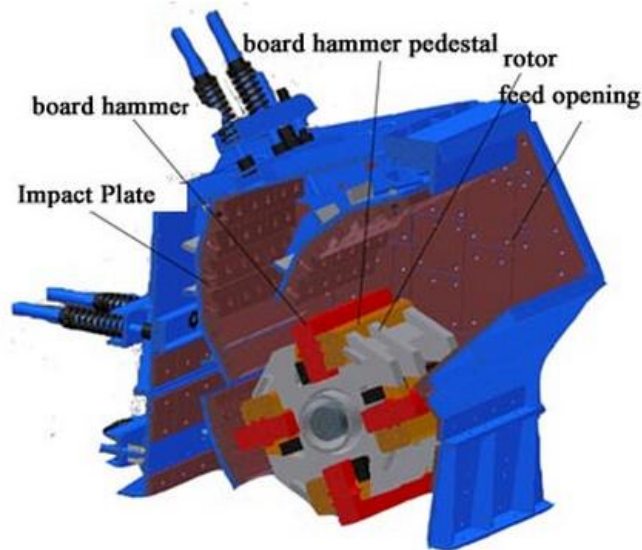


Figure 2.3 Image of an impact crusher (Stonecrusher.org, 2011)

In a concrete recycling plant, a big concern is the properties of recycled aggregates rather than the grain-size distribution. In other words, the recycled aggregates are better when they have less attached mortar and when they keep their original shape intact. The differences between jaw crushers and impact crushers when recycling concrete are compared by Hansen (1992). It is concluded that jaw crushers perform better than impact crushers because jaw crushers set at 1.2-1.5 times the maximum size of original aggregates will crush only a small proportion of original aggregates in the old concrete. Impact crushers, on the other hand, will crush mortar and original aggregate particles alike, which produces recycled coarse aggregates with a lower quality. Because when an aggregate is thrown to the impact plate by the rotor, there is usually a relative small contact surface between the aggregate and the impact plate with relatively a big impact energy, thus cracks will generate during the crushing process. Those two crushers both have their own advantages and disadvantages. It is suggested by Hansen (1992) that jaw crushers should be used for the processing of plain or lightly reinforced concrete while heavy impact crushers are more suitable for normal or heavy reinforced concrete. The main disadvantage of impact crushers is high wear and tear therefore higher maintenance costs.

For the purpose of concrete recycling, normally, on the demolition sites the individual debris size should be reduced to a size which can be accepted by the primary crusher of the recycling plant. It requires the close cooperation of all the parties involved in the recycling process. Hansen (1992) suggested the maximum particle size for large stationary plants is 1200 mm while for mobile plants it is 400-700 mm. This value, of course, varies with the machinery of the recycling plants as well as the desired efficiency of the company.

In order to obtain high quality recycled concrete aggregates with less mortar attached to the surface and with relatively intact shape, a novel jaw crusher was invented by Schenk Concrete Consultancy. This machine was used in this research. More details of the jaw crusher is described in Chapter 3.7 of this thesis.

2.2 Hydration of Portland cement

Portland cement is the most widely used type of cement. In this research, mainly Ordinary Portland Cement (OPC) is discussed. The chemical reactions of hydration and dehydration are the key factors for thermally treated concrete recycling. This chapter will describe the chemical composition of OPC and its hydration process.

2.2.1 Production of ordinary Portland cement

The process of manufacturing Portland cement can be described simply as ‘grind two times, bake once’. Limestone and clay are the main raw materials of Portland cement. As for the chemical component, limestone mainly contains CaCO_3 ; clay mainly has Al_2O_3 and SiO_2 in it. At the beginning, both of the materials are ground and mixed proportionally. At this stage, small quantities of some other materials such as iron oxide (Fe_2O_3) may be necessary to be added in the mixture. The mixed raw materials are then sent to a rotary kiln, in which the temperature reaches as high as $1450\text{ }^\circ\text{C}$. After a few hours, the key components such as calcium silicates and aluminates are formed. The raw materials are converted into cement clinker which is combinations of oxides. When the clinker from the kiln is cooled down, a certain percentage of gypsum (calcium sulfate dihydrate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is added to regulate setting of the paste. Then the mixture of clinker and gypsum is grinded to fine powder. The final product is called Ordinary Portland Cement (OPC) (Illston and Domone, 2001; Taylor, 1997).

2.2.2 Chemical notation and composition

The final Portland cement product has four main compounds or so called phases which are Alite, Belite, Aluminate and Ferrite. In cement chemistry, abbreviations and notations for these compounds are used for convenience. These are shown in Table 2.1:

Table 2.1 Oxides and their mass fraction in a typical commercial concrete (ENCI CEM I 42.5 N)

Abbreviation	Oxide	Name	CEM I 42.5 N [%mass]
C	CaO	Lime	63.0
S	SiO ₂	Silica	20.0
A	Al ₂ O ₃	Alumina	5.0
F	Fe ₂ O ₃	Iron oxide	3.0
\bar{S}	SO ₃	Sulfur trioxide	2.2
RO		Rest oxides	5.7
LOI		Loss on ignition	1.1

In Table 2.1, RO stands for some other oxides other than oxides above, for instance MgO, K₂O, Na₂O etc.. LOI means loss on ignition. The values of the mass fractions can vary between cement sources and types.

The Bogue method is a solution of a set of linear simultaneous equations, each giving the total fraction of one of the main phases. In Bogue's equations, x stands for the mass fraction of each component. Based on the mass fraction in Table 2.1, the mass fraction content of the four phases can be calculated according to Bogue's equations (Table 2.2) (Taylor, 1997), the results are shown in Table 2.3. One thing to be addressed is that when calculating with the Bogue equation, the lime content has to be deduced because of an estimated 0.7% of free lime existing in the cement composition (ENCI).

Table 2.2 Bogue's equations:

$$\begin{aligned}
 x_{C_4AF} &= 3.043x_F \\
 x_{C_3A} &= 2.650x_A - 1.692x_F \\
 x_{C_3S} &= 4.072x_C - (7.600x_S + 6.718x_A + 1.430x_F + 2.852x_{\bar{S}}) \\
 x_{C_2S} &= 2.867x_S - 0.754x_{C_3S} \\
 x_{C\bar{S}} &= 1.701x_{\bar{S}}
 \end{aligned}$$

Table 2.3. Five main compounds of Portland cement and their mass fractions (ENCI CEM I 42.5 N)

Phase	Name	Molecular formula	Abbreviation	% by weight
Alite	Tricalcium silicate	3CaO.SiO ₂	C ₃ S	57.5
Belite	Dicalcium silicate	2CaO.SiO ₂	C ₂ S	11.8
Aluminate	Tricalcium aluminate	3CaO.Al ₂ O ₃	C ₃ A	8.2
Ferrite	Tetracalcium aluminoferrite	4CaO.Al ₂ O ₃ .Fe ₂ O ₃	C ₄ AF	9.1
Gypsum	Calcium sulphate dihydrate	CaO.SO ₃ .2H ₂ O	C \bar{S} H ₂	3.7

2.2.3 Hydration process

Cement hydration is an exothermic process; when the cement is mixed with water, hydration begins. One thing that can stop this process is the ambient temperature: once the temperature drops to as low as -10 °C,

the hydration process stops completely (Illston and Domone, 2001). The rate of heat output is an index of the rate of hydration reaction: the higher the heat output is, the higher the hydration rates are, Figure 2.4 shows the reaction speed variation with time after mixing.

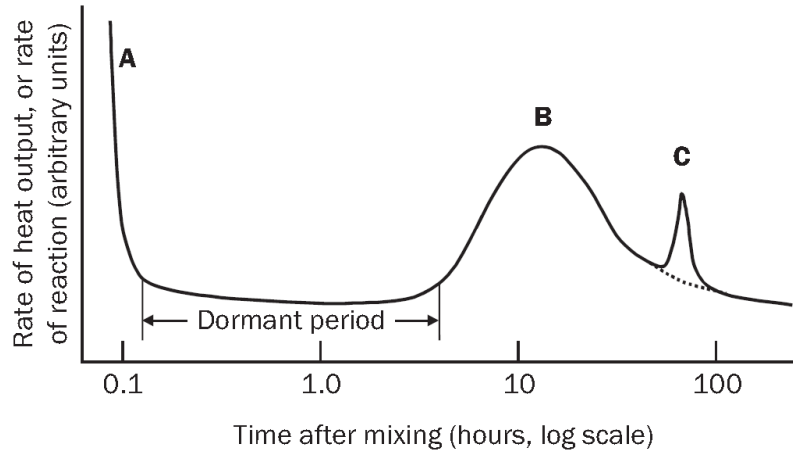


Figure 2.4 Typical rate of hydrating cement paste at constant temperature (Forester, 1970).

As it can be seen in Figure 2.4, the cement hydration has three peaks. The reasons that caused this phenomenon are the different characteristics of the cement phases.

The peak (A) is mainly attributed to the hydration of calcium sulphate hemihydrates, which is added to the cement clinker during the grinding process in the form of gypsum. The hydration of gypsum is a process that releases a large amount of heat:



The purpose of adding gypsum in concrete is that the aluminate phase in the cement reacts with water very violently. Gypsum acts as a set-controlling agent which retards the stiffening of the paste and solves the problems of flash set. The heat comes from some other sources as well, like the hydration of free lime, heat of solution and the initial reactions of the aluminate compound. Ettringite is formed during this process (Illston and Domone, 2001).



Equation 2.2 is the initial reaction; at the later stage, when the gypsum is consumed, the ettringite is gradually transformed to calcium monosulfoaluminate.

Alite is the most important constituent of Portland cement clinkers, constituting 50-70% by weight. It reacts relatively quickly with water, producing the so-called C-S-H gel and calcium hydroxide:



The hydration products usually referred to as C-S-H gel are extremely important for the engineering properties of concrete and give the hardened cement its strength and stiffness. In the heat evolution Figure 2.4, this reaction leads to the heat output peak (B). The accumulation of calcium hydroxide makes the hardened cement paste highly alkaline, with a pH between 12.5 and 13, which has a significant influence on the durability of concrete constructions exposed to the acid environment.

Aluminate constitutes 5-10% of normal Portland cement clinkers. It reacts rapidly with water, and can cause rapid setting at the early age when water and cement are mixed. Usually, the gypsum is about 5-6% by weight of the cement. If gypsum is consumed before C₃A, a peak (C) then occurs 2 or 3 days after the hydration starts. Peak C may not happen if there is enough gypsum in the unhydrated cement.



Belite or C₂S reacts much more slowly than alite, but the reaction products are the same. Belite hydration contributes little to the strength during the first 28 days, but substantially to the further increase in strength that occurs at later ages.



If we compare the two chemical reactions of alite and belite, on a mass basis, both silicates require approximately the same amount of water for their hydration, but C₃S produces more than twice as much Ca(OH)₂ as is formed by the hydration of C₂S on a mass basis. Alite and belite form the bulk of unhydrated cement; they are the most important components to the engineering properties of concrete.

The ferrite phase makes up 15% of normal cement clinkers. The rate at which it reacts with water appears to be somewhat variable, so the composition of the final products is imprecise and variable. Final products vary approximating to C₃(AF)C₃ \bar{S} H₃₂ and C₃(AF) \bar{S} H₁₆ respectively (Illston and Domone, 2001; Taylor, 1997; Neville, 2002). The rate C₄AF reacts with water appears to be variable, but in general is high initially and low or very low at later stage.



Table 2.4 Cement hydration products at different relative humidity (RH) (Taylor, 1997)

Name	Saturated state (100% RH)		Dried state (11% RH)	
	Formula	[g/mol]	Formula	[g/mol]
C-S-H gel	$C_{1.7}SH_{3.2}$	213.09	$C_{1.7}SH_{2.1}$	193.27
Calcium hydroxide	CH	74.00	CH	74.00
Hydroxy-AFm	C_4AH_{22}	722.72	C_4AH_{13}	560.58
Monosulfoaluminate (SO₄-AFm)	$C_4A\bar{S}H_{14}$	658.62	$C_4A\bar{S}H_{10}$	586.56
Ettringate (AFt)	$C_6A\bar{S}_3H_{36}$	1327.34	$C_6A\bar{S}_3H_{12}$	894.98
Hydrogarnet	$C_6AFS_2H_{18}$	1042.67	$C_6AFS_2H_8$	862.47

2.2.4 Factors that influence the hydration of cement

There are a lot of factors that can influence the hydration of cement. In the following section, factors like cement fineness, temperature, water/cement ration etc. will be discussed.

Physical properties such as surface area of the cement particles can influence the early age hydration significantly. Portland cements are fine powders which have particle sizes between 2 and 75 μm and specific gravity of about 3.14. The particle size determines the surface area: for the same weight of cement, the smaller the particles are, the higher the total surface area is. With a small particle size, the contact surface between water and cement grain increases, which leads to a higher hydration speed.

Compaction of the mixture is very important for the hydration process as well. A better compaction will increase the contact surface between water and cement through minimizing the air intake and decrease the porosity of the hardened cement paste. A better compaction should lead to an increased strength of the hardened cement paste.

Temperature will also affect the hydration of cement. It is concluded (Illston and Domone, 2001) that increasing temperature accelerates the hydration of all the four main cement constituents. A rise in the curing temperature is beneficial for the early strength of concrete (Neville, 2002). The reason can be that the higher temperature reduces the length of the dormant period in (Figure 2.4) so that the overall structure of the hydrated cement paste can be formed much earlier. However, although the hydration can be sped up by a higher curing temperature, the adverse effects of a high early temperature on later strength have been found (Neville, 2002). Because the high temperature leads to a rapid initial rate of hydration, there is not enough time for the diffusion of the hydration products away from the cement particles and thus causes a high concentration of the hydration products in the vicinity of the cement grains. As a result, a high temperature retards the subsequent hydration and produced a non-uniform distribution of the hydration products within the paste and adversely affects the long term strength. In pursuing high early strength, especially in the precast concrete plants, steam curing, autoclaving and even infrared-radiation are being widely used to speed up the early age hydration. As for the low temperature, hydration will continue with decreasing temperature until about $-10\text{ }^\circ\text{C}$ when it stops completely. It is reported (Neville, 2002) that $13\text{ }^\circ\text{C}$ is the optimum temperature during the early life of concrete that will lead to the highest strength at later age.

The water/cement ratio is a factor that can influence the hydration significantly. Water/cement ratio can affect both the hydration degree and the strength of the final hardened sample. There are two conditions

that should be noticed: the condition of insufficient water and the condition of insufficient volume (Illston and Domone, 2001). When the water/cement ratio is lower than 0.43, full hydration can never occur without other water sources. It is called the condition of insufficient water. If there is an available external source of water, for instance, the cement or concrete is immersed in water, full hydration can occur with such a water/cement ratio. However, the water/cement ratio of 0.43 is a theoretical value. In practice, without the external water source, the hydration will cease somewhat before all of the available water is consumed. In reality, an initial water/cement ratio of about 0.5 is required for full hydration.

It is called the condition of insufficient volume when the water/cement ratio is lower than 0.38 (Illston & Domone, 2001). At this condition, hydration will be stopped before completion, even if when an external source of water is available. The reason is that at the water/cement ratio of about 0.38, the volume of hydration products exactly matches the volume of the fresh cement and water. Therefore, there is not enough space for further hydration. The water/cement ratio determines the porosity of the hardened cement paste. Excess water may lead to high porosity of the hardened cement paste, resulting in a lower strength. The water/cement ratio has to be properly calculated during each concrete composition design in order to achieve the desired strength and suitable workability.

2.3 Fly ash and slag

Fly ash and slag are two kinds of industrial by-products; both of them are being used in construction industry as cement replacement materials. Fly ash and slag have some common characteristics with Portland cement. For instance, their particle size range is similar to or smaller than that of the Portland cement; they can be involved in the hydration reactions; their chemical compositions are similar to that of Portland cement but with different proportions. Based on the similarities, they can be added to the cement clinker to make fly ash cement or slag cement. Moreover, they can be supplied as individual materials directly to the concrete at mixing (Neville, 2002).

Fly ash and slag are closely related with a term: pozzolanic behavior. Illston (2001) defines that “a pozzolanic material is one which contains active silica (SiO_2) and is cementitious in itself but will, in a finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form cementitious compounds.” The key to the pozzolanic behavior is the structure of the silica; this must be in a glassy or amorphous form with a disordered structure, which is formed in a rapid cooling from a molten state. A uniform crystalline structure which is formed in slower cooling, such as is found in silica sand, is not chemically active. Fly ash and slag are usually used to partly replace Portland cement to make the binder materials for construction industry.

2.3.1 Fly ash

Fly ash is the fine ash obtained after the burning of pulverized coal used in coal-fired power plants. There are standards (EN 450) for the selection of fly ash; only fly ash with certain particle size, chemical composition and loss on ignition values can be used in concrete production. The standards classify fly ash based on the lime content. Using fly ash in new concrete can be beneficial for the environment, since landfilling is not required and less cement needs to be produced. Fly ash has a spherical shape which makes it suitable for improving the workability of concrete (see Figure 2.5).

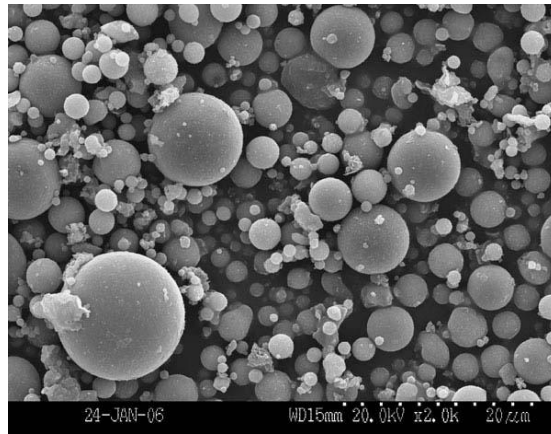


Figure 2.5 Class F fly ash sample as viewed via SEM at 2000× magnification (University of Kentucky, 2012)

The other advantage of using fly ash in concrete is that it slows down the hydration process and so reduces the hydration heat accumulation, which makes it good for bulky constructions to reduce heat related cracking. However, the hydration of fly ash does take a longer time to start than Portland cement. In the construction industry, it is always wanted to reach a high construction speed and a higher economical return. If concrete has a slow strength because of the addition of fly ash, it can be unfavorable for the project. Fraay etc. (1989) conclude that it is because the glass material in fly ash is broken down only when the pH value of the pore water is at least above 13.2. This leads to the topic of fly ash activation. Fly ash can be activated through either a physical way or a chemical way. Physical activation is to grind the fly ash particles into smaller sizes. When the particles are ground to a surface area of 4000 cm²/g, it hardly can increase its activity by further decreasing the particle size. It is worth mentioning that the major chemical components of fly ash are the acidic oxides, which are easily activated in an alkaline environment. That is the reason alkali hydroxide or salts are often used as chemical activators of fly ash.

2.3.2 Slag

Slag or ground granulated blast furnace slag (ggbfs) is the unwanted part of molten ore from the steel industry suddenly cooled down by water. It is ground to a similar fineness as Portland cement. Slag has a higher silica content and a lower calcium content than Portland cement. The most important thing is that it contains active amorphous silica required for the pozzolanic reaction. An alkali environment is necessary for the activation of those glassy particles.

Both fly ash and slag have lower specific gravities than Portland cement, and when they are used to substitute cement on a weight-for-weight basis will result in a greater volume of paste. Both high lime fly ash and slag contain significant quantities of CaO which also take part in the hydration reactions. Therefore, both of them are to a certain extent self-cementing, thus they are not a true pozzolan (Illston and Domone, 2001). The presence of cement acts in a way like a catalyst to speed up the hydrations of fly ash and slag. When fly ash and slag are used to replace Portland cement, sufficient Portland cement has to be in the mixture in order to supply enough calcium hydroxide for the secondary reactions. Actually, not only Portland cement can be used to activate fly ash and slag, dehydrated cement paste can also be used to activate them. This will be explained in the following section.

2.4 Dehydrated cement paste

2.4.1 Dehydration of the hydrated cement paste under high temperatures

Studies (Carette et al., 1982; Handoo et al., 2002) show that if concrete is subjected to high temperatures, for instance, in case of fire, there is a huge loss of strength and other engineering properties. Carette et al. (1982) tested cylinder specimens with a dimension of 100 mm by 200 mm subjected to temperatures up to 600 °C. There was a gradual loss of compressive and splitting-tensile strengths of concrete when they are cooled down. There are many changes in the physicochemical, mineralogical characteristics of concrete that cause this strength loss, but it is mainly due to the dehydration of the hydrated cement phase after sustained high temperature (Alonso and Fernandes, 2004; Shui and Xuan, 2009; Alarcon-Ruiz et al., 2005; Castello et al., 2004).

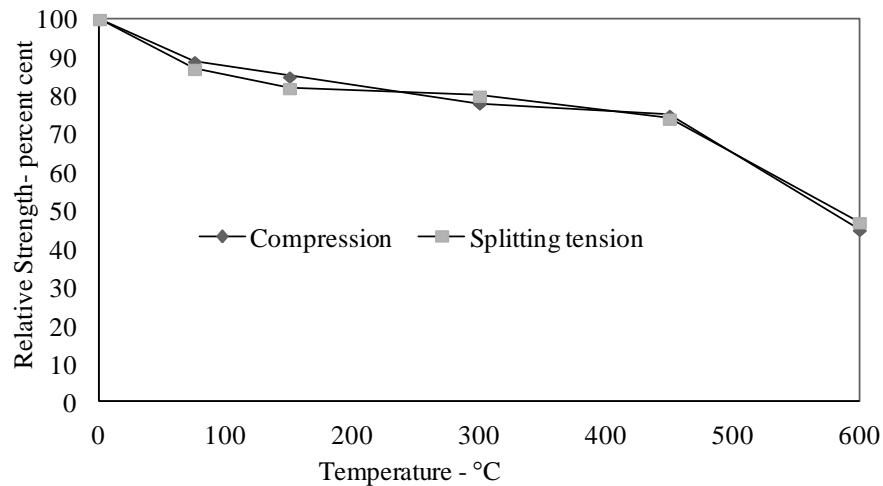


Figure 2.6 Influence of exposure to a high temperature on the compressive and splitting-tensile strengths of concrete (Carette et al., 1982)

Different chemical components show different characteristics when hydrated cement paste is subjected to high temperatures:

Ettringite was reported to be thermally decomposed at a very low temperature of 90 °C by Castello et al. (2004). The starting temperature for the decomposition of ettringite is even lower than that of the complete loss of free water which is at a temperature between 105 °C and 110 °C. Alonso et al. (2004) concluded in a graph that ettringite became dehydrated abruptly after the temperature of 100 °C.

The C-S-H gel is reported (Castello et al., 2004) to start dehydration between the temperatures of 200 °C to 400 °C. Handoo et al. (2002) employed scanning electron microscopy (SEM) for investigation. They concluded that the morphological changes of the C-S-H gel mainly happened beyond 600 °C. Alonso et al. (2004) conducted a systematic study of concrete subjected to high temperatures. Their research results show that the C-S-H gel starts to dehydrate slightly as early as 100 °C to 200 °C, dehydrating gradually

with a rising temperature. They observed that from 600 °C to 750 °C, the solid phases contain mainly dehydrated C-S-H (new nesosilicate), CaO, anhydrous phases and dehydrated ettringite.

Portlandite is an important cement hydration product. It is reported (Tayyib, 1989) that portlandite decomposes at a relatively low temperature of about 400 °C. Castello et al. (2004) employed the neutron diffraction method to study the composition and microstructural changes of cement paste upon heating. The authors concluded that portlandite decomposed abruptly at a temperature between 530 °C and 560 °C, transforming into lime. Alarcon-Ruiz et al. (2005) used thermal analysis to assess the effect of temperature on cement paste. The authors concluded that the dehydration and the decarbonation reactions were irreversible in the cement paste and can be used as tracers for determining the temperature history of concrete after a fire exposure. The dehydroxylation reaction of the portlandite is reversible, since it seems to rehydrate rapidly after a heat treatment.

From the literature study above, conclusions can be made for the relationship between dehydration and temperature.

Table 2.5 Transformation of cement paste with relation to temperature

Temperature	Transformation
<110 °C	Loss of physically bound water
~450 °C	Dissociation of portlandite
~570 °C	Transformation of quartz
~750 °C	Dissociation of carbonates
~1050 °C	Loss of chemically bound water

Shui et al. (2009) studied the cementitious characteristics and the relative rehydration capability of dehydrated cement paste (DCP). The samples of hydrated cement paste (HCP) were grinded to the powder size smaller than 75 µm. It was found out that the higher the dehydration temperature of DCP is, the higher the required water of DCP to maintain the same standard consistency is. The results show water of standard consistency increases from 32% for the samples at the room temperature up to 68% for the sample that thermal treated at 900 °C. The initial setting and final setting time were decreasing with the increase of temperature. For DCP samples treated at 800 °C, the initial setting time is as low as 17 min, which is slightly lower than the sample which was subjected to 900 °C. The compressive strength tests of DCP show that up to 800 °C, the compressive strengths of rehydrated DCP reach the maximum value for both early ages and 28 days. The authors concluded that the cementitious capability of DCP strongly depends on the dehydration temperature that the pre-heated HCP is subjected to.

It is found that the hydrated cement paste became reactive again if subjected to high temperatures. The rehydration ability of the dehydrated cement paste can possibly be used again in engineering practices for replacement of cement. More research has to be done on the dehydration of recycled concrete fines (RCF) with particle sizes smaller than 150 µm which are mainly composed of hydrated cement paste and silica. All the studies show that thermal treatment is a possible way for smart recycling of concrete aggregate fines.

2.4.2 Possible use of dehydrated cement paste

The hydrated cement paste can be thermally treated to become dehydrated cement paste. How to use those dehydrated cement paste in new cement or concrete is an emerging topic for researchers. Shui et al. (2008) did a lot of research on DCP, illustrating that the hardened cement paste subjected to a temperature of 500 °C mainly composed of dehydrated C-S-H, C₂S, CaO, partially CH and noncrystal dehydrated phases. If the pre-heated cement paste meets water again, the initial hydrated products of fine recycled concrete aggregates are recovered to original hydration products such as C-S-H gel, ettringite and CH. However, the microstructure of the rehydration products is looser than that of the ordinary cement paste. Another research result (Shui et al., 2009) demonstrates that DCP requires more water than ordinary Portland cement to keep the same standard consistency. The setting time of DCP paste decreases with the increase of the dehydration temperature. The 28-day compressive strength of DCP is much lower than the original cement. Moreover, the hydration process is much faster than the ordinary cement (Shui et al., 2009). The hydration products are alkaline because of the existence of calcium hydroxide. If it is associated the rehydration process of DCP with the hydration properties of fly ash and slag, it can be interesting to use dehydrated cement paste as the activator or starter for fly ash and slag.

Shui et al. (2011) used DCP treated with the temperature of 650 °C along with CaSO₄, CaCl₂ and Ca(OH)₂ as the activator of fly ash, the results were impressive, the compressive strength of the new cementitious material with a certain proportion of DCP and fly ash was higher than 60 MPa when the original cement strength was 42.5 MPa. This research result is encouraging for future application of DCP in engineering practices. However, in their research, the samples were steam cured, which makes quite a difference from the samples cured under the room temperature. The other difference was that in their research, pure cement paste was used for research purpose instead of real fine recycled aggregates from concrete. In the case of using real recycled concrete fines, there is a large amount of fine particles from silica sand and gravel mixed in the hydrated cement paste during the crushing process. The inactive quartz will reduce the starter effect of the pozzolanic reactions. How to separate the low silica fraction from high silica fraction of the recycled concrete fines is important for the dehydrated cement paste used as starter. In a word, it is very inspiring to use dehydrated cement paste along with industry by-products to make new binding materials for constructions.

Based on the previous description, it can be assumed that a binder system composed of thermally treated concrete fines (mainly composed of silica and dehydrated cement paste) and fly ash or slag can be a possible replacement for ordinary Portland cement; this assumption will be investigated by experiment in this thesis.

2.5 Use of RCA in concrete: Properties of fresh and hardened mortars and concrete

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 (Hansen, 1992). The first three applications are basically a down cycling which uses those recycled aggregates in low grade applications. The fourth one, to apply RCAs in new concrete, is the most favorable one with respect to the environment protection and economical benefits. In this section, the use of recycled aggregates in new concrete will be discussed.

Attached mortar is the main concern for using the recycled concrete aggregates in new concrete; it accounts for the principal difference between RCAs and natural aggregates. Recycled concrete aggregates with less attached mortar are considered to have a higher quality than those with a higher mortar content. Aggregates with a certain amount of mortar or cement paste attached on them have a lower density and higher water absorption because of the porosity of the paste (Hansen, 1992). 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 (Etxeberria et al., 2007). Etxeberri et al. (2007) 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% by mass of the aggregates. Hansen (1992) reported a value up to 60% for 4-8 mm coarse recycled aggregates and 65% for the 0-0.3 mm filler fraction. Padmini et al. (2009) reached a similar conclusion. The recycled particles smaller than 2 mm are considered not usable to make new concrete by some researchers because of the large amount of attached cement paste (Meyer, 2009; Hansen, 1992). The attached mortar content of the recycled concrete aggregate is called residual mortar content (Abbas et al., 2009). The authors developed a quick laboratory test method to determine the attached mortar content in order to serve as quality control of recycled concrete aggregates. Mulder et al. (2007) reported a thermal treatment method to obtain aggregates with only 2% of hardened cement paste remaining attached to the sand and gravel grains. Not all the researchers think the attached cement paste is a disadvantage. Kou et al. (2009) 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 a universal agreement (Lo et al., 2008; Etxeberria et al., 2007; Corinaldesi and Moriconi, 2009; Padmini et al., 2009; Evangelista and de Brito, 2007; Sagoe-Crentsil et al., 2001; Shi-Cong and Chi-Sun, 2009; Kou and Poon, 2009). This is because of the lower density and higher porosity of cement paste attached to the recycled aggregates. Lower density can be an advantage because the concrete incorporating recycled concrete aggregates has a lower density, thus reducing the dead load of the structure.

Because of the attached mortar or cement paste on the original aggregates, the water absorption value of the recycled aggregates is much higher than the natural aggregates (Kim et al., 2011; Lo et al., 2008; Sim and Park, 2011; Etxeberria et al., 2007; Corinaldesi and Moriconi, 2009; Padmini et al., 2009; Evangelista and de Brito, 2007; Sagoe-Crentsil et al., 2001; Shi-Cong and Chi-Sun, 2009; Kou and Poon, 2009). There are several factors influencing the water absorption value of the recycled concrete aggregates. Padmini et al. (2009) concluded that water absorption increases with an increase in the strength of the parent concrete. The fine recycled concrete aggregates have a higher mortar or paste content than coarse recycled concrete; they are also reported to have a higher water absorption value than the coarse recycled concrete aggregates by some researchers (Sim and Park, 2011; Corinaldesi and Moriconi, 2009; Padmini et al., 2009). Higher water absorption will lead to higher water/cement ratio if the recycled particles are used in new concrete production in order to obtain the same workability. It also influences the setting behavior and strength development of new concrete. Hansen (1992) suggested using pre-soaked aggregates for the production of recycled aggregate concretes in order to maintain a uniform quality during the concrete production. Water absorption of coarse and fine recycled aggregates must be determined in the laboratory before any mix design of recycled aggregate concrete can be attempted.

Some researchers (Tam et al., 2008) suggested that current European standard is not suitable for determining the water absorption value of recycled aggregates. Three reasons are argued: Firstly, drying at 105 ± 5 °C to obtain the oven-dried mass of aggregates may remove chemically bound water in mortar crystals; Secondly, recycled aggregates need a longer time to reach full saturation, for instance, as long as 120 hours rather than 24 hours suggested in the current standard; Thirdly, using cloth or towel to obtain saturated surface dry sample may rub away cement paste attached to the aggregates surface. A more appropriate method for determining the water absorption of recycled aggregates by using hydrostatic weighing approach was brought forward by Tegguer (2012).

In this thesis, the use of recycled concrete aggregates in new concrete will be discussed in three groups: recycled concrete fines (RCF): particles smaller than 150 μm ; recycled concrete sand (RCS): particle sizes between 150 μm and 4 mm which are the aggregates that are used to replace the fine natural aggregates; recycled concrete gravel: particles that are bigger than 2 mm, those particles are used to replace the coarse natural aggregates.

2.5.1 Use of recycled concrete fines smaller than 150 μm

There are few studies focused on the recycled concrete particles smaller than 150 μm . Normally, recycled particles of this size are considered as the unusable fraction or of little use as filler (Hansen, 1992). Particles smaller than 150 μm are a similar size to cement particles; the main components are the cement hydration products, unhydrated cement, particles of original fine aggregates and crushed quartz particles from the original aggregates. Because the hydration of cement is not complete, particles of this size have a certain but not completed degree of hydration (Shui et al., 2009). There is a possibility to use recycled particles of this size as the replacement of cement in new concrete production. Shui et al. (2009; 2008) used a thermal treatment method to make dehydrated cement paste. The rehydration of the dehydrated cement paste can obtain a certain degree of strength, especially when mixed together with fly ash (Shui et al., 2011). The steam curing accelerated the pozzolanic reaction of fly ash; the mixture obtained quite high strength (60 MPa) in the end. It can be seen that recycled concrete particles smaller than 63 μm can be used as the binder material in new concrete but just some prior treatments are needed.

There is also the possibility to relinker recycled fine particles smaller than 63 μm to a certain proportion in the cement production (Mulder et al., 2007). Before the relinkering, the particle purification may be needed to eliminate the inactive silica from the particles which will disturb the chemical composition of cement. The dehydrated cement paste together with a certain proportions of other raw materials, especially limestone, can be used to produce a high grade cement. The dehydration of hydrated cement paste will release mostly H_2O instead of CO_2 in the conventional cement production (Schneider et al., 2011). Moreover, the required dehydration heat is lower than decarbonation heat in the conventional cement production (Friedrich, 2005). Therefore, it is expected that less energy will be required in the cement production with relinkering of recycled concrete fines smaller than 63 μm .

2.5.2 Use of recycled concrete sand to replace fine natural aggregate

Fine aggregate is defined to be the aggregates smaller than 4 mm in the European Standard EN 12620: 2002. The fine fraction of recycled concrete aggregates is believed to jeopardize the properties of new concrete. Researches show that it is possible to use recycled concrete sand in the production of new

concrete without sacrificing the concrete fresh and hardened properties significantly (Corinaldesi and Moriconi, 2009; Evangelista and de Brito, 2007; Kou and Poon, 2009).

Some researchers studied the fresh properties of the use of recycled concrete sand in replacement of fine natural aggregates; however, their observations do not seem to be consistent with each other. Kim et al. (2011) reported that the workability decreases with increasing replacement ratio. Khatib (2005) 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 (2009) 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. More water was added with the increase of fine recycled aggregates replacement, in the end, a better slump test result was obtained for higher replacement because of the water absorption of recycled aggregates at 10 min only reaches 51% of the 24 h absorption value. Corinaldesi and Moriconi (2009) 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 (1992) first 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 (2011) 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 (2005) 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; higher shrinkage was also observed with increasing replacement ratio. Shi-Cong et al. (2009) found that at a fixed water/cement ratio, fine recycled aggregates decreased the compressive strength and increased the drying shrinkage of the concrete. Kim et al. (2011) found the use of fine recycled aggregates in new concrete generally decreased the compressive strength with an increasing replacement ratio, while for 25% replacement, the compressive strength was even higher than the control group; the flexural strength decreased with an increasing replacement ratio but acceptable for 25% and 50% replacement ratio. Evangelisa et al. (2007) used fine recycled aggregate to replace sand from 0.074 mm-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 contamination 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.

2.5.3 Use of coarse recycled aggregate to replace coarse natural aggregate

Recycled coarse aggregates are considered easier to use than fine recycled aggregates in new concrete production because they have less attached mortar and a lower water absorption value. However, lots of studies have shown that coarse recycled aggregates are still somewhat inferior to conventional aggregates in new concrete production. Their applications in new concrete are limited to less than 30% replacement of natural aggregates as suggested by some researchers (Hansen, 1992; Kasai, 1993).

For the fresh properties of coarse recycled aggregates concrete, based on Hansen's (1992) review, in order to achieve the same workability, recycled concretes produced with coarse recycled aggregate and natural sand required approximately 5% more free water than control concretes produced with corresponding natural aggregates. Approximately 15% more free water was required when both fine and coarse recycled aggregates were used, which means coarse recycled aggregate did not influence the water/cement ratio as much as fine recycled aggregate. If recycled aggregates were employed in dry conditions, the workability of the concrete was greatly reduced because the water absorption of recycled aggregates made the concrete set faster than concrete with wet recycled aggregates (Hansen, 1992). This means that in actual concrete production, it may be necessary to pre-saturate the recycled concrete aggregates in order to avoid rapid setting and a workability loss of the fresh recycled aggregate concrete. Etxeberri et al. (2007) used slightly more additives for coarse recycled aggregate concrete than conventional concrete in order to achieve the same slump. Corinaldesi et al. (2009) and Tabsh et al. (2009) found that coarse recycled aggregate concrete needed more water to maintain the same slump value without admixtures, thus resulting in a lower concrete strength. Based on previous research, it is generally believed that the incorporation of coarse recycled aggregate will be detrimental to the workability of the fresh recycled aggregate concrete. It is necessary to determine the water absorption value of the coarse recycled aggregate in the laboratory before their use in new concrete production.

Eguchi et al. (2007) used recycled coarse aggregate in new concrete aiming for structural use. They concluded that the concrete compressive strength and elastic modulus decreases with increasing coarse aggregates replacement ratio. Nixon (1978) made a conclusion based on his review of earlier research; he concluded that the compressive strength of recycled aggregate concrete in some cases can be up to 20% lower compared with the strength of control mixes of conventional concrete. Hansen (1992) and Padmini et al. (2009) concluded that the compressive strength of recycled aggregate concrete depended on the strength of the original concrete and the water-cement ratio. If the same strength as parent concrete is to be achieved, recycled aggregate concrete required lower water-cement ratio and higher cement content. In some cases, recycled aggregates concrete made with coarse recycled aggregate and natural sand obtained approximately the same strength and in some cases even higher strength than corresponding control concretes made entirely with natural aggregates. Etxeberria et al. (2007) found that using recycled coarse aggregates in new concrete required a higher amount of cement to reach the same strength as original concrete which made it not economical to make high strength concrete with coarse recycled aggregate since cement is the most expensive material in the concrete mixture. Recycled concrete aggregates size is another factor that can influence the recycled aggregate concrete strength; Padmini et al. (2009) found

that the achieved concrete strength increased with increasing in the maximum grain size of recycled aggregate used.

From the above literature study, the following conclusions can be drawn:

- The principle difference between recycled concrete aggregates and natural aggregates is the cement paste that are remaining on the recycled concrete aggregate surface. The fine recycled aggregates generally have higher cement content than coarse recycled aggregates. High cement paste content leads to low density of the recycled aggregates;
- Using both of recycled concrete sand and recycled coarse aggregates will decrease the fresh performance of the concrete, this is due to the higher water demand of recycled aggregates. Superplasticizer can be used to improve the workability of the recycled aggregate concrete.
- The compressive strength of coarse recycled aggregate concrete depends on the strength of the original concrete;
- The compressive strength of recycled aggregate concrete also depends on the maximum size of recycled aggregate used;
- In order to obtain the same strength as the original concrete, more cement is needed.

2.6 Concrete recycling and green building certificate

Green building certificates are the certificates that show new constructions or major renovation projects are doing better than normal buildings in the aspects of energy saving and environmental protection as well as the indoor air quality. The certificates are evaluated and given by third party organizations. Buildings with green labels have positive environmental images to the community and are considered more valuable in the estate market than ordinary buildings under the same conditions. LEED and BREEAM are the most widely applied green building certificates worldwide. Both LEED and BREEAM have clauses which specifically state the use of recycled concrete aggregates adds 1 or more points to the total score. Actually, use of recycled concrete aggregates in projects will be awarded more points to the total certificate score directly or indirectly, for instance in LEED:

Leadership in Energy and Environmental Design (LEED) is a point rating system released by the U.S. Green Building Council (USGBC) to evaluate the environmental performance of a building and encourage market transformation towards sustainable design. It is widely being used in United States and increasingly being applied in other countries like China and India. The system is credit-based, allowing projects to earn points for environmentally friendly actions taken during the construction and the service of the buildings. LEED 2009 (USGBC, 2011) has 100 base points, 6 possible points for innovation in design and 4 regional priority points. So, the total score is 110 points. A minimum of 40 points is required in order to be certified. Silver, gold and platinum levels are also available; a higher score will end up with a higher level of certificate. Table 2.6 lists the certificates in relationship with their points. LEED 2009 addresses 7 topics: Sustainable Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), Indoor Environmental Quality (IEQ), Innovation in Design (ID) and Regional Priority (RP).

Table 2.6 LEED 2009 levels and required points.

Certificate levels	Required Points
Certified	40-49
Silver	50-59
Gold	60-79
Platinum	>80

Table 2.7 shows the possible LEED points that can be gained by incorporating recycled concrete aggregates in the new construction or major renovation projects. Some of those points are apparently linked to the use of recycled concrete; however, some of them are the points that can be attributed to the properties of ordinary concrete that can be replaced by recycled aggregate concrete. For instance, the use of high thermal mass property of concrete in energy saving; the solar reflectance coefficient of concrete in reducing thermal island effect are the same properties as ordinary concrete. The explanations of each credit that is related to recycled concrete are presented.

Table 2.7 Recycled concrete contributes to LEED points (LEED 2009)

Topics	Credit Name	Possible Points
Sustainable Sites	Credit 3 Brownfield Redevelopment	1
	Credit 5.1 Reduced Site Disturbance, Protect Open Space	1
	Credit 5.2 Reduced Site Disturbance, Development Footprint	1
	Credit 6.1 + 6.2 Storm water Management, Rate & Quality	2
	Credit 7.1 Heat Island Effect, Non-Roof	1
Energy and Atmosphere	Credit 1 Optimize Energy Performance	1-19
Materials and Resources	Credit 1.1 Building Reuse, Maintain Existing Shell	1-3
	Credit 2 Construction Waste Management	1-2
	Credit 3 Material Reuse	1-2
	Credit 4 Recycled Content	1-2
	Credit 5 Regional Materials	1-2
Innovation in Design	Credit 1.1 Innovation in Design, Reduce Cement Content	1-5
	Credit 2 LEED Accredited Professional	1
Total		42

Brownfield Redevelopment: Binder materials are used to solidify and stabilize contaminated soils and reduce leach concentrations to below regulatory levels. Stabilization refers to the chemical changes between the stabilizing agent and the hazardous constituent. Cementitious materials like Portland cement,

lime, fly ash, slag, clay and gypsum are used as binding agents in brownfield redevelopment. Thermally treated recycled concrete fines are proved to have binding effect (Shui et al., 2008), they can be used for brownfield redevelopment (Shima et al., 2005).

Site Development-Protect or Restore Habitat: Parking garages within buildings instead of paved outdoor parking can be used to limit site disturbance. The parking garage within the building can be made from recycled aggregate concrete.

Site Development-Maximize Open Space: Parking garages on the underground floor of the building made of recycled aggregate concrete can help reducing the footprint of the development. It helps to maximize open space around the building.

Storm water Design-Quality Control: Managing storm water runoff can limit the disruption and pollution of natural water flows. Using pervious concrete pavements will reduce the rate and quantity of storm water runoff because they increase infiltration of storm water. Coarse recycled concrete aggregates are suitable to make the pervious concrete pavement. The reason is pervious concrete contains coarse aggregate, little or no fine aggregate, and insufficient cement paste to fill the voids between the coarse aggregate. Because of a high volume of voids, water can flow through easily.



Figure 2.7 Pervious concrete pavement

Heat Island Effect-Non roof: This credit requires materials with a solar reflectance value of at least 0.3 for at least 30% of the site's non-roof impervious surfaces such as sidewalks, parking lots and access roads. The ratio of reflectance can be met by using light color concrete instead of asphalt for the non-roof impervious surfaces (Levinson and Akbari, 2002). In that case, recycled aggregates concrete can be perfectly used for the non-roof applications. Increasing the solar reflectance of a paved surface keeps it cooler in the sun, thereby decreasing the ambient air temperature. Lower air temperatures decrease demand for cooling energy and reduces urban heat island effect.

Optimize Energy Performance: Energy performance of a building is one of the most important factors in judging if a building is green or not. LEED 2009 awards up to 19 points to this credit when the energy

simulation result of a candidate new building is 48% less than a baseline building. Heating and cooling consumes a lot of energy when the building is in service. In order to save energy on heating and cooling, wisely using of the thermal mass of concrete along with good insulation and some other measures can save a lot of energy (Balaras, 1996; Fallahi et al., 2010). However, the points to be gained depend on the building type, climate, baseline building in the standard and several other factors. Recycled aggregate concretes can be used in projects as much as possible to increase thermal mass of the whole building if necessary.

Construction waste management: This credit is received for diverting construction and demolition debris from land fill disposal. The goal is to direct the recyclable recovered resources back to the manufacturing process and to use reusable materials to the appropriate sites. It is awarded based on handling at least 50% by weight of the above listed materials. When concrete buildings are demolished, concrete is recycled and the obtained aggregates are used for other uses rather than go to the landfill. When 75% of the waste is diverted, two points are awarded.

Materials reuse: The goal of this credit is to reuse building materials and products to reduce demand for new raw materials and reduce waste, thereby lessening impacts associated with the extraction and processing of virgin resources. The target is to use salvaged materials such as beams and posts, flooring, paneling, doors and frames, bricks and decorative items, etc.. There is the possibility to construct the new building based on the concrete structure of the existing building on the same site. Although the concrete used is not from a concrete recycling plant, it is even better than that.

Recycled content: The intent of this credit is to encourage the building contractors to incorporate more recycled content materials, thereby reducing the extraction and processing of virgin materials. Apparently, this credit is the most notable one for encouraging the use of recycled concrete aggregates. The requirement is that the sum of postconsumer recycled content plus half of the post industry recycled content constitute at least 5% of the total value of the materials in the project. Recycled concrete aggregates are considered as postconsumer material, supplementary cementitious materials such as fly ash, silica fume and slag are considered post-industrial material.

Regional materials: The regional materials credit supports the use of local materials and reduced transportation distances. In this credit, regional materials means materials that are extracted and manufactured within 800 kilometers of the project site for a minimum of 10% of the total material value. Normally, concrete are recycled in the nearby plants which are most likely situated in the same city or close by cities from the construction site. When the recycled concrete aggregates are used directly in ready-mixed concrete, there is always a maximum transportation distance which is definitely less than 800 kilometers between a construction site and the concrete plant. So, recycled aggregate concretes can help to obtain maximum points for this credit.

Innovation in design: There is 1-5 points as bonus points rewarding the innovation in design. Credit can be achieved by using significant, measurable environmental performance using a strategy not addressed in the LEED 2009. Those bonus points are somewhat tricky to get comparing to the others. An example is given by USGBC that allows for an innovation credit if 40% less cement is used than in typical construction, or if 40% of the cement in concrete is replaced with slag cement, fly ash or both. It is

possible to achieve this target by using slag cement in the structure, thermally treated recycled concrete fines together with pozzolanic materials instead of cement in the less important part of the building (Shui et al., 2011).

LEED Accredited professional: This requirement is easy to achieve if there are LEED accredited professionals at the concrete recycling plants who take part in the certificate application processes.

The above arguments are based on the descriptions in the LEED 2009 manual (USGBC, 2011). The points listed in Table 2.7 show there are maximum 42 points related to the use of recycled concrete in the candidate buildings for LEED certificates. However, some of those points can only be achieved under specific circumstances and being carefully planned and designed. There is a significant contribution to the final certificate level if most of the 42 points are to be awarded since 40 points are enough to guarantee a LEED certificate. Still, it is wise to use recycled concrete elements in new constructions for environment protection purposes, no matter if the building is going to be green labeled or not.

BREEAM is another leading green building rating system widely used in Europe. It's similar to LEED's scoring system, it is not described in detail here. There is one clause (BREEAM, 2011) that states that the use of recycled aggregates will be awarded 1 point in the section of Waste Part. It prescribes that in order to get 1 point, minimum 25% of recycled aggregates shall be used in structural frame, floor slabs, concrete road surfaces and building foundations; more than 50% of recycled aggregates should be used in bitumen or hydraulically bound base, binder, and surface courses for paved areas and roads and pipe bedding; 100% of recycled aggregates shall be used in gravel landscaping. If more percentage of recycled aggregates is being used, bonus innovation credits will be awarded. Of course, there are similar indirect points to be awarded when recycled concretes is being used. In short, there is a promising prospect for more recycled concrete to be used in the future green buildings.

3 Laboratory techniques and measurement methods

3.1 Particle size analysis

Particle size distribution (PSD) is an important parameter for concrete mix design. In the concrete mix design, for the larger particles, the grading of aggregates determine the PSD. PSD of the concrete aggregate design has a significant influence on the mixture workability and the amount of required cement paste. For the coarse aggregates and sand, dry sieving is used to determine the PSD; the sieving method is described by standard EN 933-1. A stack of sieves were built into a tower in the order of decreasing sieve openings with the smallest sized sieve on bottom, followed by a metal tray. The grading can be expressed either in the way of percentage of mass passing of each sieve or in the way of cumulative passing. Cumulative passing of a sieve size is obtained by adding of the all the percentages of materials kept by sieves below the current sieve.

For binder material and filler materials, particles smaller than 100 μm are influenced by electrostatic forces to a large extent which makes it inappropriate to use dry sieving (Hüsken, 2010). In this research, PSDs for fine particles are measured by a Mastersizer 2000 laser granulometer (Figure 3.1).

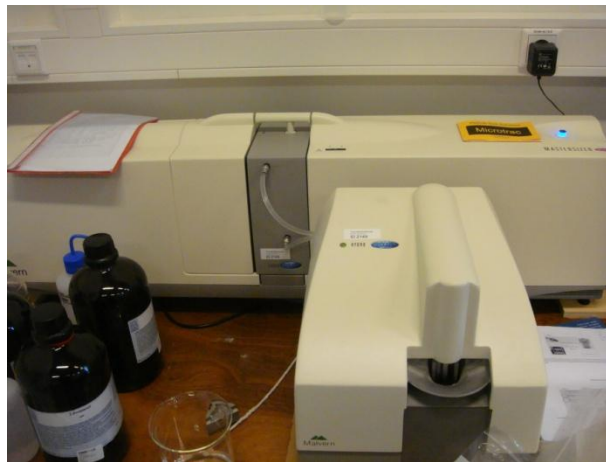


Figure 3.1 Mastersizer 2000 for PSD measurement

First, the fine particle powder was dispersed in an appropriate solution which will neither react with the powder nor dissolve the powder. In this research, isopropanol was used as the dispersant for cement, fly ash, slag and recycled concrete fines PSD analysis. Then, the particle size distribution was measured by means of laser diffraction analysis (LDA) for the particles in the micro range. The accuracy of the LDA analysis depends on the wavelength of the used beam, which makes it inaccurate for particles under 0.1 μm in the case of the Mastersizer 2000 (Malvern, 2007). The LDA method for measuring PSD is prescribed in the standard ISO 13320:2009. PSDs of the fine particles are expressed in cumulative passing as a function of the logarithm of the particle sizes in this research.

3.2 Specific density measurement

The measurement of specific density of solid materials by using the pycnometer method is described in standard EN 1097-6 for fine and coarse aggregates and in EN 1097-7 for fines. The specific density ρ_{spe} is calculated by:

$$\rho_{spe} = \frac{M_{sol}}{V_{sol}} \quad (3.1)$$

where M_{sol} is the mass of the solid material and V_{sol} is the true volume of the solid material. The mass of the material is determined by a balance (Figure 3.2 left), the true volume of the material is determined by using a pycnometer model AccuPyc II 1340 (Figure 3.2 right).



Figure 3.2 Balance (left) and gas pycnometer (right)

Because of recycled concrete aggregates have sealed pores inside them, these will be counted in the volume of the aggregates when submerged in water. In order to remove the influence of the pores, all the recycled aggregates were milled into powders by a ball mill.

The principle of the gas pycnometer is that it measures the amount of displaced gas. The gas used for this experiment is helium which is a noble gas that will not react with the aggregates. All the obtained powders were dried in oven at the temperature of 70 °C for 24 hours before density measurements. The reason of using 70 °C rather than 105 ± 5 °C as described in the standard is that phases existing in the recycled aggregates like ettringite disassociate at temperatures lower than 100 °C (Castello et al., 2004). The C-S-H gel will also decompose slightly at the temperature of 100 °C (Alonso & Fernandes, 2004).

3.3 X-Ray Diffraction

X-ray radiation was discovered over a century ago by Wilhelm Conrad Röntgen. X-rays have wavelengths in the angstrom range (10^{-10} meter) which is sufficiently energetic to penetrate solids (Ramachandran & Beaudoin, 1999). The characteristic of x-rays makes it suitable to probe solid internal structure without damaging the material. It is now widely used in material analysis and evaluation for element analysis (x-ray fluorescence (XRF)) and phase composition studies (x-ray diffraction (XRD)). In this research, XRD was used to identify the crystalline phases in the thermal treated fines.

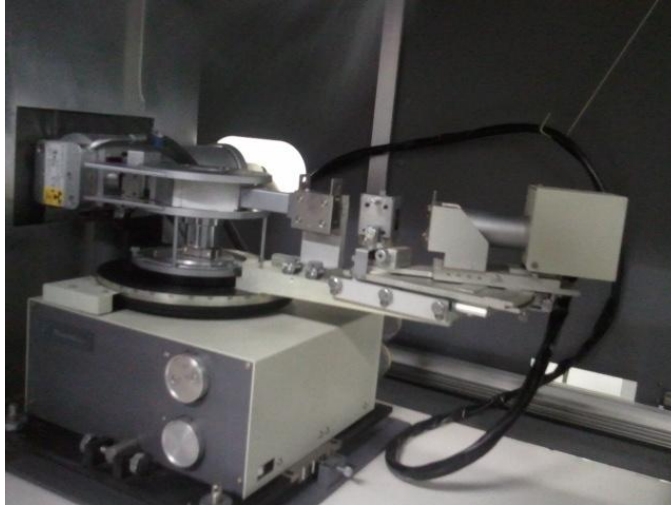


Figure 3.3 Rigaku X-ray machine

Solid matter can be categorized into two types: the first type is amorphous, the second type is crystalline. The atoms of amorphous materials are assembled together in a random way, for example, glasses and liquids are amorphous materials. As for crystalline material, the atoms or molecules are arranged in an orderly, regular, periodic manner. About 95% of all solids can be described as crystalline. More than 60,000 different crystalline phases can be determined by using XRD.

X-ray diffraction is the elastic scattering of x-rays by atoms in a periodic lattice (Ramachandran & Beaudoin, 1999). When the scattered x-rays are in phase, the obtained diffraction pattern will have a constructive interference. The principle of X-ray diffraction constructive interference is explained by using the Bragg's law:

$$n\lambda=2d\sin\Theta \quad (3.2)$$

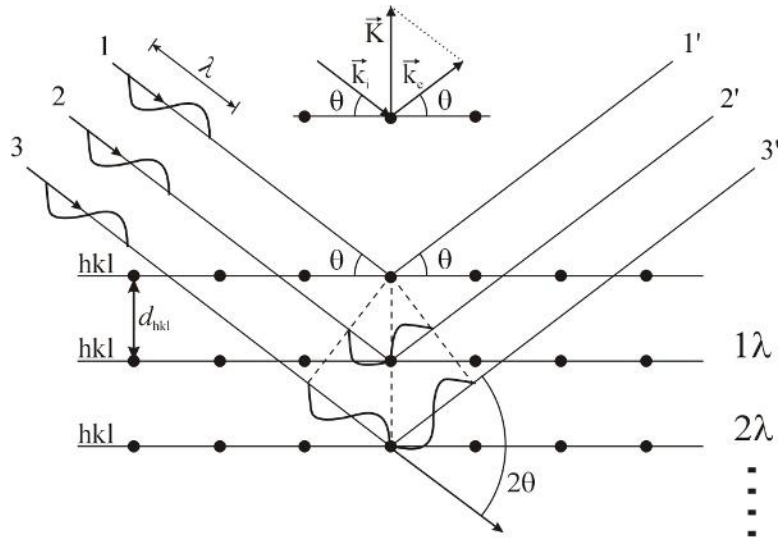


Figure 3.4. Bragg's law principle (Leuven University Website, 2012)

In Equation 3.2, Θ is the angle between the incident beam and the lattice plane, λ is the wavelength of the X-rays, d is the characteristic spacing between the crystal planes, n can be any positive integer.

Each crystalline phase has its own plane distance, which can be considered as the fingerprint of the material. For each crystalline material, at specific angles, constructive interference peaks can be observed. When the wavelength of the beam is known, based on the measured angles, every single crystallographic phase can be determined by search and match from the Powder Diffraction File (PDF) from the International Center for Diffraction Data (ICDD).

The sample preparation is important for each XRD measurement. Smooth surface and evenly distribution of the crystalline phases in the homogeneous sample are important for powder diffraction. If possible, the powders are better grinded into particles close to 5 μm . The grinded powder is then pressed into a sample holder in order to obtain a smooth and flat surface.

3.4 Thermalgravimetric analysis (TGA)

A Netzsch simultaneous analyzer, model: STA 449 F1 was used to obtain Thermogravimetric (TG) and Differential Scanning Calorimetry (DSC) curves of the recycled concrete fines.



Figure 3.5 Netzsch TG-DSC analyzer model STA 449 F1

TG measures weight changes in a material as a function of temperature under a controlled atmosphere. The atmosphere has to be controlled to avoid reactions with the measured material. In the case of recycled concrete fines, with the elevated temperature, the cement paste keeps dehydrating. The crystal water and chemically bound water keep being evaporated with elevated temperature. Some compounds are dissociated during the heating process, for instance, calcium hydroxide and calcium carbonate. In this research, the machine temperature reaches up to 1100 °C.

DSC measures the amount of heat required to increase the temperature of a sample and the reference sample as a function of temperature. Some chemical reactions and physical transformations can be either endothermic or exothermic under which more heat will need to flow in or flow out respectively from the sample. In the case of recycled fines, the phase change of quartz and some other chemical reactions can be recorded by DSC.

3.5 Calorimetry

A TAMAir Micro calorimeter model 3116-2 was used for the calorimetry study. A calorimeter is a device used to measure the heats of chemical reactions and physical transformations. TAMAir is an isothermal, heat conduction calorimeter with the measurement accuracy of milliwatts. The model used in this research has eight channels mounted together with a single heat sink block. Each channel has two wells, one for the sample and the other for a reference. Water was used as the reference in this research. During each measurement, the sample and the reference were placed in 20-ml ampoules and kept in the selected channel. The calorimeter is located in a laboratory room with controlled temperature and air flow. The real time heat flow data is recorded and transferred to a connected computer.



Figure 3.6 TAMair Micro calorimeter

Thermally treated recycled concrete fines possess a certain hydration ability when put into contact with water again. In this research, thermally treated fines treated at different temperatures were mixed with water at a fixed water/binder ratio and the hydration heat as measured continuously for the beginning 7 days.

3.6 Properties of concrete: fresh and hardened state

Concrete is being used in a process of mixing, transporting, place, consolidating and curing. Both the fresh state and hardened state properties of concrete are important for the construction industry.

During the fresh state stage, concrete undergoes the most intensive changes; the mixture can be molded into different shapes. Actually, a lot of parameters are used to describe the fresh state properties of concrete, but engineers are mostly concerned about the workability or consistence of concrete. The workability as described by Neville (2002) is “that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished”. Concrete in its fresh state must flow into the formwork and flow through the reinforcement with the assistance of available compaction equipment. This fluidity has to be within a certain limit in order to keep the concrete in a homogeneous form. The presence of voids in concrete has to be avoided since the voids can reduce the concrete strength significantly. When pursuing a good workability, however, segregation of mortar from coarse aggregates has to be prevented. The main parameter that contributes to concrete workability is the water content of the mix. Besides that, the sizes of aggregates, their grading, shape and texture also play roles in the concrete workability.

Strength is the most important property of concrete in the hardened state. Concrete structures are designed to support a certain imposed load. Hardened concrete has a high compressive strength but a relatively low tensile strength. In this study, both compressive strength and flexural strength will be studied.

In order to make sure concrete in its fresh and hardened states can fulfill the expected target, different tests are being used. Some of those tests are included in European standards which make them widely

used. For the fresh state properties, the Vicat test and the slump test will be described in detail. For the hardened state properties, compressive strength and flexural strength will be presented.

3.6.1 Flow table test

In this research, mortar samples were made to test the strength. The consistence of fresh mortars were measured by using the flow table method. European standard EN 1015-3: 2007-05 describes the method of measuring the consistence of mortar samples. It is said in this standard that there is a linear correlation between this method and the plunger penetration method as described in EN 1015-4.

The apparatus used in this method includes a flow table, a truncated conical mould, a tamper and a ruler. The conical mould is made of stainless steel with smooth inner surface. The mould is 60 mm \pm 0.5 mm in height, 100 mm \pm 0.5 mm at the bottom and 70 mm \pm 0.5 mm at the top.

The fresh mortar is prepared in accordance with EN 1015-2. The mould is put in the center of the flow table disc, with the conical mould damped and dried. The mortar is filled in the mould in two layers with each layer tamped by 10 strokes. Extra mortar on top of the mould is cleaned and the top surface smoothed. The mould is then lifted vertically and slowly. The mortar is spread out by jolting the flow table 15 times at a frequency of one jolt per second.

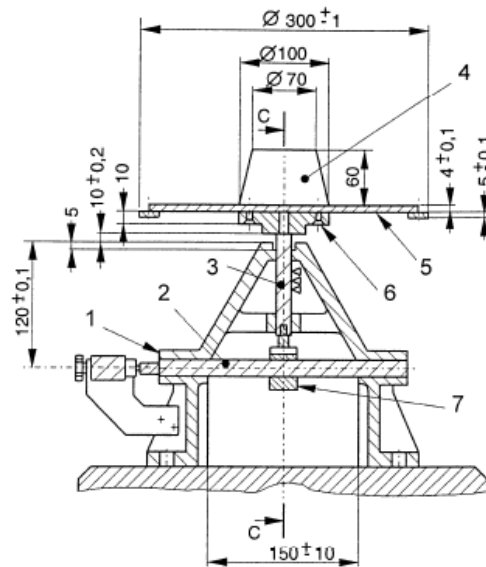


Figure 3.7 Flow table apparatus (adapted from EN 1015-3)



Figure 3.8 Flow table test

The diameter of the mortar cake is measured in two directions perpendicular to each other with the result to the nearest mm. Each mortar sample is tested for two times; the final consistence is determined by the mean value of the two measurements.

3.6.2 Flexural strength

The testing of flexural strength of mortar samples is prescribed in the European Standard EN 196-1.

The test starts from preparing mortar samples. The sand used in this test has to be CEN Standard sand in accordance with EN 196-1 5.1.2 and 5.1.3. The cement used for the test has to be isolated from ambient air in order to avoid the reactions with the moisture content in the air. Drinking water, distilled or deionised water can be applied in the mixture. The mass proportion of the three components is 0.5: 1: 3 for water, cement and sand respectively. The size of experimental specimens is 40 mm × 40 mm × 160 mm. Three specimens are made in the same batch. For each batch of mixture, the weight of each component material is provided by the standard as (225 ± 1) g of water, (450 ± 2) g of cement and (1350 ± 5) g of sand. There is a standardized procedure for the mechanical mixing, moulding and demoulding of the mortar specimens prescribed in EN 196-1.

The cured specimens then can be used for flexural tests at 1 day, 2 days, 3 days, 7 days and 28 days; there is a specified time range for the tests in the standard. The testing itself should follow a standard procedure.

A flexural strength testing machine or a suitable compressive testing machine with an adapter can be used to measure the flexural strength. The dimensions of the experimental setting is shown in Figure 3.9; the dimensions are in millimeters.

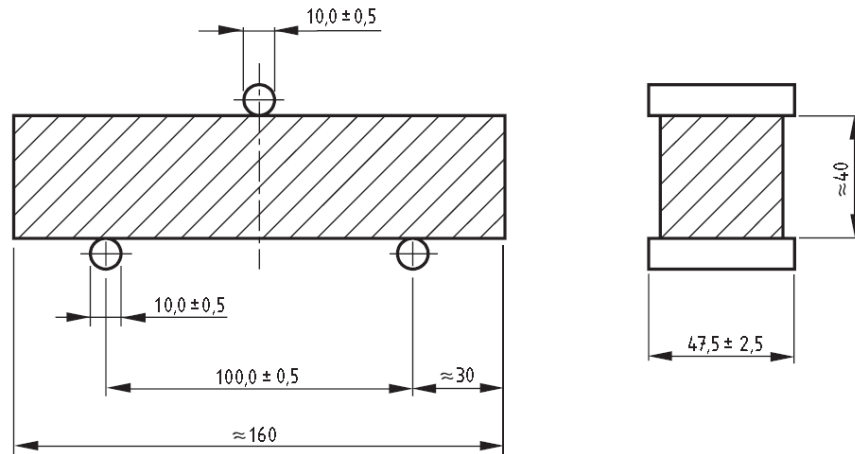


Figure 3.9 Dimensions of the flexural strength test (adapted from EN 196-1: 2005)

When doing this test, attention should be paid to the surface of the specimen; only the side surfaces can be used in contact with the supporting and loading rollers. The load is subjected at an increasing rate of (50 ± 10) N/s until the fracture of the specimen. The flexural strength R_f in is calculated with the following formula (EN 196-1: 2005):

$$R_f = \frac{1.5 \times F_f \times l}{b^3} \quad (3.3)$$

where:

R_f is the flexural strength;

b is the side of the square section of the prism, 40 millimeters;

F_f is the load applied to the middle of the prism at fracture;

l is the distance between the supports, 100 millimeters.

The flexural strength test result is calculated as the arithmetic mean of the three individual prism results; the result is recorded to the nearest 0.1 MPa. The remaining halves of the specimens will be used for compressive strength test if needed, and shall be kept in a damp condition until the compressive test.

3.6.3 Compressive strength

The mortar compressive strength test is prescribed in EN 196-1: 2005.

The samples used for the compressive strength can be obtained either from the prism halves from the flexural strength test or by other ways to split the mortar samples prepared in the same way as for flexural strength. The compressive strength test machine is described in EN 196-1: 2005 sections 4.8 and 4.9. Each prism half is placed laterally to the platens of the machine, with the side surfaces on the top and bottom side to avoid stress concentration. The load is increased at a rate of (2400 ± 200) N/s until fracture.

The compressive strength R_c is calculated by the formula provided by EN 196-1: 2005:

$$R_c = \frac{F_c}{1600\text{mm}^2} \quad (3.4)$$

where

R_c is the compressive strength;

F_c is the maximum load at fracture, in newtons;

1600 mm^2 is the area of the auxiliary plates ($40 \text{ mm} \times 40 \text{ mm}$).

The compressive strength arithmetic mean results are calculated based on the six individual results, to the nearest 0.1 MPa. The results within the 6 results that vary more than $\pm 10\%$ from the average result are discarded; this process is repeated until the final average compressive strength is obtained.



Figure 3.10 Mortar strength test machine (left) and fractured mortar sample (right)

3.7 Smart crushing principle

The crusher used in this research is a jaw crusher specially designed for concrete recycling. It is a patented invention under the world patent number of: WO 2011/142663 (Schenk, 2011). This is a test model modified based on a commercial jaw crusher Fritsch pulverisette 1 model II. The technical facts of Fritsch pulverisette 1 model II are listed in Table 3.1.

Table 3.1 Technical facts of jaw crusher Fritsch pulverisette 1 model II.

Working principle	Pressure
Grinding parts	Fixed and movable crushing jaws
Maximum feed size	95 mm
Final fineness	1 – 15 mm
Eccentric oscillations	308 movements/min
Max continuous throughput	200 kg/h
Electrical details	400 V, 50 – 60 Hz, 2780 watt

The picture of the modified machine (left) and the perspective side view of the jaw crusher (right) in operation as described in the patent file (Schenk, 2011) are shown in Figure 3.11.

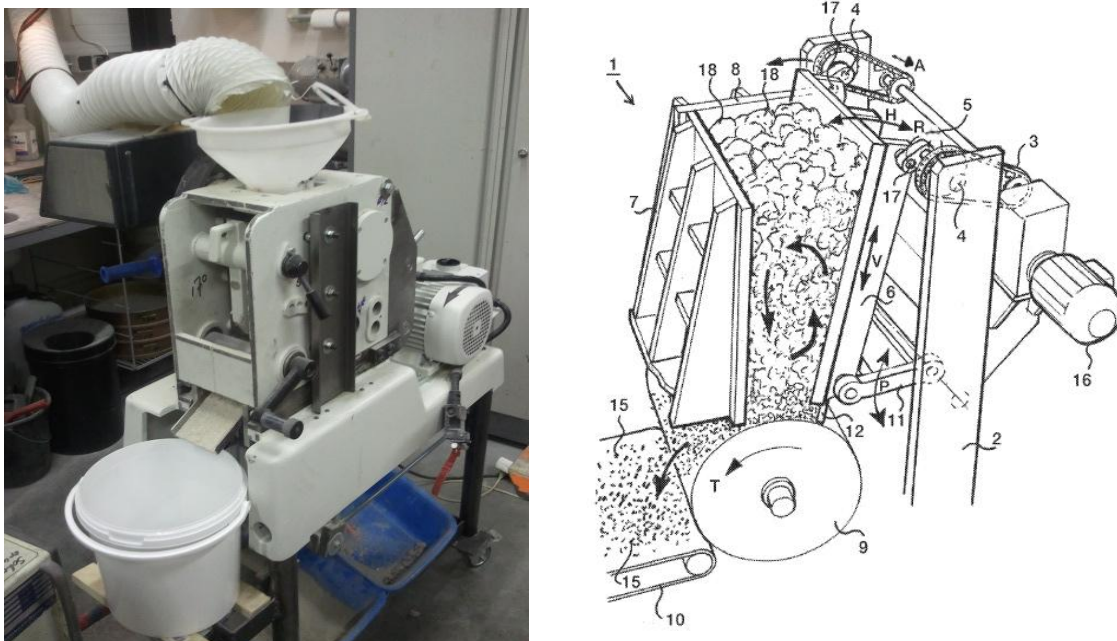


Figure 3.11 The jaw crusher used in this research (1. Crusher; 2. Frame; 3. Drive belt; 4. Rotating shaft; 5. Cam; 6. Crushing plate; 7. Static plate; 8. Side wall; 9. Drum; 10. Discharge belt; 11. Pivot arm; 12. Scraper; 15. Small fractions of concrete; 16. Motor; 17. Rotating shaft; 18. Concrete.)

In this patent the new crusher is described as a separating machine rather than a jaw crusher by the inventor. 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 case of concrete, it will crush through aggregates. Moreover, the aggregates reclaimed by conventional crusher are not “clean”: there is still a relatively large amount of mortar attached to the surfaces. The principle of this machine can be described as follows: concrete is not homogenous, therefore, different parts have different strengths. The coarse aggregate is

usually the strongest part in concrete, the compressive strength of aggregates varies depending on the kind of rocks. Neville (2002) concluded that a good average value of the crushing strength of aggregates is about 200 MPa. However, some weak rocks like marble are also used as concrete aggregates which have an average compressive strength of 117 MPa. The weakest part in the concrete is cement paste, usually less than 50 MPa in most of the constructions. Therefore, the key to separate the cement paste from the concrete aggregate by not breaking the aggregates is to exert a pressure between the highest strength of the cement paste and the lowest strength of the aggregates. It is said in the patent file (Schenk, 2011) that, in order to separate concrete into the composite materials without the risk of the components themselves being damaged; the force exerted on the matter between the crushing plates has to be lower than a critical limit of 100 N/mm^2 .

In order to separate the concrete component materials based on their properties, some new features which are not being used by existing jaw crushers are used in this invention. In the following paragraphs, differences between a conventional jaw crusher and the current invention will be discussed.

Consider a large piece of concrete falling into the mouth of a conventional jaw crusher. It is nipped by the jaws, which are moving reciprocally close to each other. The time of one “bite” has to be enough for the materials to fall to a new position before being nipped again. The concrete falls until it is arrested. The moving jaw closes on it, quickly at first and then more slowly with increasing power towards the end of the stroke. Then, the swing jaw moves repetitively away from and toward the static jaw. Therefore, the concrete is crushed to small particles until they can be released by the gap between the two jaws.

The crushing of a jaw crusher can be distinguished into free crushing and choked crushing. During each “bite” of the jaws the concrete swells in volume due to the creation of voids between the particles. The crushed concrete particles are falling into a gradually reducing cross-sectional area of the crushing chamber. If the moving jaw moves with an amplitude big enough for the crushed materials to go through the chamber, it is called free crushing. Choked crushing will happen when the volume of materials arriving at a particular cross-section is greater than that are leaving. In choked crushing, particles break each other while in free crushing; concrete is crushed by the jaws only (Wills & Napier-Munn, 2006). The inter-particle communication of the choked crushing can lead to the excessive production of fines. Severe choking can lead to the damaging of the crusher. As for crushing concrete, inter-particle communication is wanted for cleaning the mortar attached to the aggregate surfaces while damaging of the machine is to be avoided. In the current invention, the space between the crushing jaws at the outlet opening is enlarged on purpose. The outlet opening is wide therefore it is no longer the restriction for the outlet particles. Particles that are smaller than the outlet opening can escape from the crushing chamber of a conventional crusher. Restrictions is also essential for the current invention, therefore, a rotating drum (No. 9 in Figure 3.11) is added below the out opening of the crushing jaws. This means that the mutual distance between the static jaw (No.7 in Figure 3.11) and the surface of the drum (No.9 in Figure 3.11) is the restriction of the fineness of the crushed concrete. This restriction distance is adjustable by moving the height of the drum for desired product fineness. There are several benefits for increasing the opening at the lower end of the two jaws and adding another restriction below it at the same time.

Firstly, it reduces the peak pressure. When the outlet opening of the crusher is relatively small as in the case of an ordinary jaw crusher, the force of the crushing members is exerted on a relatively small amount of matter, for instance, one gravel pebble. The pebble is pressed toward the static jaw by the moving jaw.

The contact surfaces between the pebble and the jaws are relatively small. Therefore, the contact surfaces are subjected to a high pressure which will increase the possibility of crushing through the aggregate (Refaji et al., 2010), see Figure 3.12.

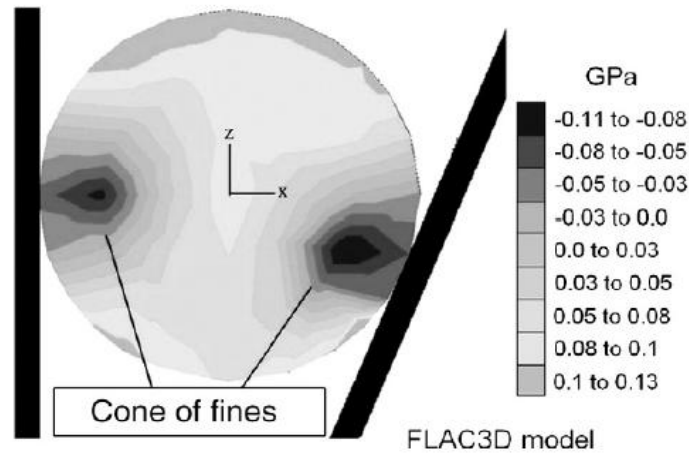


Figure 3.12. Pressure modeling at the contact surfaces between a particle and jaws (Refahi et al., 2010)

When more distance is given between the two jaws, the pressure is shared by more concrete component materials, the contact surface is increased which reduces the pressure on the contacting surfaces. Moreover, there is an increased chance to have a contact surface as mortar or cement paste which will always be crushed before a gravel pebble. A consequence is that there is a reduced chance of breaking coarse aggregates.

Secondly, it helps cleaning the aggregates surfaces. The more distance at the crusher opening, the more space there is for the matter to move. It can be understood in such a way that when only two gravel pebbles are contacting each other between the jaws, the pressure tends to crush through the pebbles. When there are three gravel pebbles in contact with each other between the two jaws, the pebble in the middle is likely to slip away under the pressure, either move upward or downward. There is more inter-communication between particles in the crushing chamber. The interacting forces are claimed to perform compound crushing by compression, tension and shearing. As a result, the cement paste or mortar is more easily scoured from the gravel pebbles. This effect is similar to the choked crushing; more fines are produced in the final products. However, unlike the choked crushing, materials will not block the crushing chamber in the new invention because the rotating drum is helping to move the materials.

Thirdly, it slows down the through-flow. In an ordinary crusher, the chamber between the inlet and outlet opening is vertical. The material once being crushed to a certain size which is smaller than the crusher opening can fall through the crushing chamber by gravity when there is no blockage. In this new invention, the restriction between the drum (No.9 in Figure 3.11) and the static jaw (No.7 in Figure 3.11) is used to restrict the product sizes and is adjustable depending on the type of the concrete. The path between the inlet and the actual outlet is no longer vertical. For that reason, the outlet restriction is also meant to hold the partially crushed/separated material between the jaws for a relatively longer time. The

advantage of the longer and high quality crushing process is that concrete is sufficiently separated into component materials rather than into smaller pieces of concrete as seen in conventional crushers.

Jaw crushers are extremely heavy-duty machines. The jaw plates themselves are smooth and are fitted with replaceable liners. Hard liners are essential for reducing wear, minimizing energy consumption and reducing the deformation of the surface at each contact point (Wills & Napier-Munn, 2006). Profiled liners with patterns on them will also influence the capacity; they can perform compound crushing such as compressive, tensile, shearing forces to the materials. Concrete is much weaker in tension than in compression, therefore power consumption and wear costs should be lower with the corrugated profiles. The liner is presented in one of the current patented crusher variations as shown in Figure 3.13 (No 47 toothed plate).

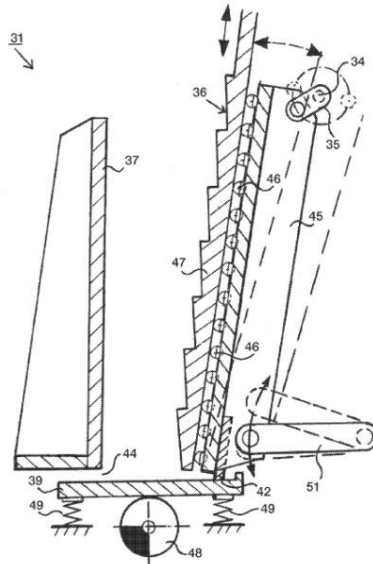


Figure 3.13 One variation of the patented crusher (Schenk, 2011)

As shown in Figure 3.13 (No. 47), a toothed plate is used as the liner. This liner is also intended to help pushing the concrete materials upward and in a rotational motion as shown in Figure 3.11. As a consequence, the materials are crushed more evenly.

The main criterion in determining the optimum speed of a jaw crusher is that particles must be given sufficient time to move down the crusher throat into a new position before being nipped again. Usually, the speed of jaw crushers lies in the range of 100-350 movements/min (Wills & Napier-Munn, 2006). In this testing model, the speed is the same as the original machine before modification which is 308 movements/min. The flow-through speed of this new invention is controlled mainly by the opening size of the restriction between the drum (No.9 in Figure 3.11) and the static jaw (No.7 in Figure 3.11), the rotational speed of the drum and the friction coefficient of the drum surface. The speed of the drum is adjustable depending on the type of material to be crushed.

The crushing amplitude is another important factor of a jaw crusher. In the conventional jaw crusher, the greater the throw, the quicker the material is removed from the crushing chamber. Higher working stress is also imparted to the machine (Wills & Napier-Munn, 2006) when a higher amplitude is used. The amplitude of the jaw swing is also adjustable when gravel pebbles are found to be crushed through. In this new invention, not only the amplitude but also the rotational motion of the moving jaw is considered. As shown in Figure 3.11, the pivot arm (No.11) at the lower part of the movable jaw (No.6) is moving up and down. The drive belt (No. 3) rotates clockwise at the upper part of the moving jaw, which drives the rotation shaft (No.4) in the clockwise direction. Through the cam (No.5), shaft (No.17) also rotates clockwise. As a result, the movable jaw (No. 6) co-displaces with the shaft. The repetitive movement of the moving jaw can be designated by arrows H and V as shown in Figure 3.11. Such a movement pushes particles upward which can prolong the crushing process.

Because of the characteristic of the above-mentioned crusher, relatively clean recycled concrete aggregates can be obtained. More fines are generated which are mainly composed of hardened cement paste powders, silica powder from sand and crushed aggregates and unhydrated cement.

4 Experiment program

4.1 Source concrete recipe

Recycled concrete fines (RCF) are mainly generated during the crushing process. A concrete recipe was designed in order to prepare the material to mimic the source concrete for recycling with known composition. Better quality can be thus ensured since no contamination materials would be mixed in the recycled materials.

The mix design has been optimized by using the mix design optimization method developed by Hüskén & Brouwers (2008). The recipe is shown in Table 4.1.

Table 4.1. Mix design of the concrete recipe

Material	Volume	Mass	Mass
	[dm ³]	[kg]	[%]
CEM I 42.5N	111.0	340.0	14.5
Limestone Powder	15.0	40.8	1.7
Sand N1	271.0	718.2	30.7
Gravel G1	248.8	659.3	28.2
Gravel G2	154.2	408.5	17.5
Water	170.0	170.0	7.3
Air	30.0		
Total	1000.0	2336.9	100.0

4.1.1 Particle size distribution of the used materials

The particle size distributions (PSDs) of the cement and limestone were determined using the Mastersizer 2000 Particle Analyzer. The PSDs of the three aggregate types were determined through dry sieving. The cumulative distributions for all the materials, the designed target line and the grading of the combined final mix are shown in Figure 4.1.

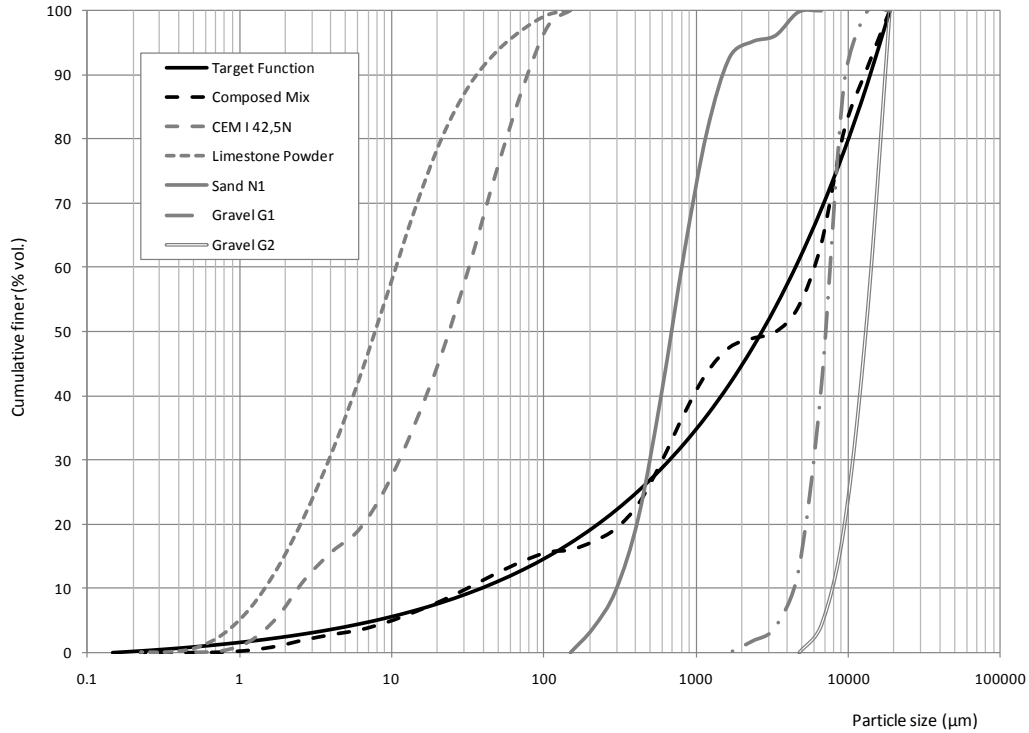


Figure 4.1. PSD of all the used materials, the target function and the final mix.

4.1.2 Water content of aggregates

The water contents of the used sand and gravels were measured and taken into account as part of the mixing water. All the aggregate fractions were dried in the oven at 105 ± 5 °C for 24 hours. The mass difference over the initial mass is the water content of the aggregates. The water/cement ratio of the mix was adjusted to take into account the water content of each aggregate type. Table 4.2 summarizes the water content of all the aggregates:

Table 4.2. Water content of aggregates, the 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

4.1.3 Concrete strength

After mixing, part of the concrete mixture was cast into cubes of 150 mm x 150 mm x 150 mm for determining the compressive strength. The rest of the mixture was cast into plastic moulds and sealed. The cubic samples were demoulded after one day and cured in water under the 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 strength of three cubes were obtained; the values are shown in Table 4.3.

Table 4.3 Compressive strength of the source concrete at the ages of 1, 3, 7, 28 and 91 days

Age (days)	Compressive strength after days (MPa)				
	1	3	7	28	91
Compressive strength (MPa)	17.59	31.74	42.70	55.15	60.52
Standard deviation (MPa)	0.07	1.00	0.97	0.38	1.86

4.2 Crushing, fractioning and analyzing the recycled concrete aggregates

4.2.1 Crushing and sieving

The concrete used for crushing was cast in plastic cups (Figure 4.2 (right)) which will fit the inlet opening of the test model smart crusher (SC) as described in Chapter 3.7. The cup concrete was firstly pre-crushed by the crusher only to reduce into smaller pieces which can better fit the inlet. After that, the concretes were crushed by another two passes of the machine. Only particles bigger than 2 mm were circulated back to the smart crusher.



Figure 4.2 Cup concrete and the dimension of the plastic cup



Figure 4.3 Concrete after pre-crushing (left), recycled concrete gravel and sand (middle) and recycled concrete fines (right)

The obtained material was sieved by using selected ISO sieves (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 20 mm. The sieving process was done as described in European Standard EN 933-1. Figure 4.4 shows the particle size distribution of the obtained materials crushed by the smart crusher (SC). In order to validate the theory of the smart crusher, the cup concrete was also crushed by a conventional jaw crusher (Retsch type: BB2/A) for 1 time (RCA I) and for 10 times (RCA II). Figure 4.6 shows the particle size distribution of the obtained materials smaller than 2 mm.

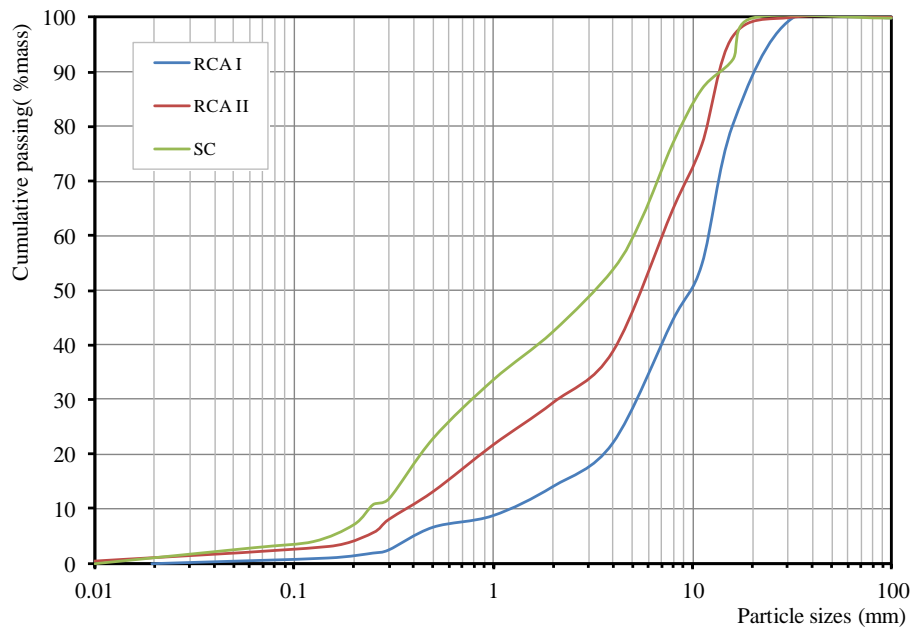


Figure 4.4 PSD of the crushed material, SC, RCA I and RCA II on a logarithmic scale.

It can be seen from Figure 4.4 that the smart crusher crushing 2 times obtained smaller materials than the conventional crusher 10 times. Figure 4.4 shows that the SC generated 33.7% by mass particles smaller than 1 mm, RCA I produced only 8.8% by mass smaller than 1mm while RCA II obtained 21.7% by mass of materials in the same size range, which means SC I produced 4 times more particles under 1 mm as that of RCA I. It can be concluded that the smart crusher can better separate cement paste from concrete aggregates than a conventional crusher. In order to compare the PSDs of fine materials, the PSD of the materials smaller than 1 mm is magnified in Figure 4.5.

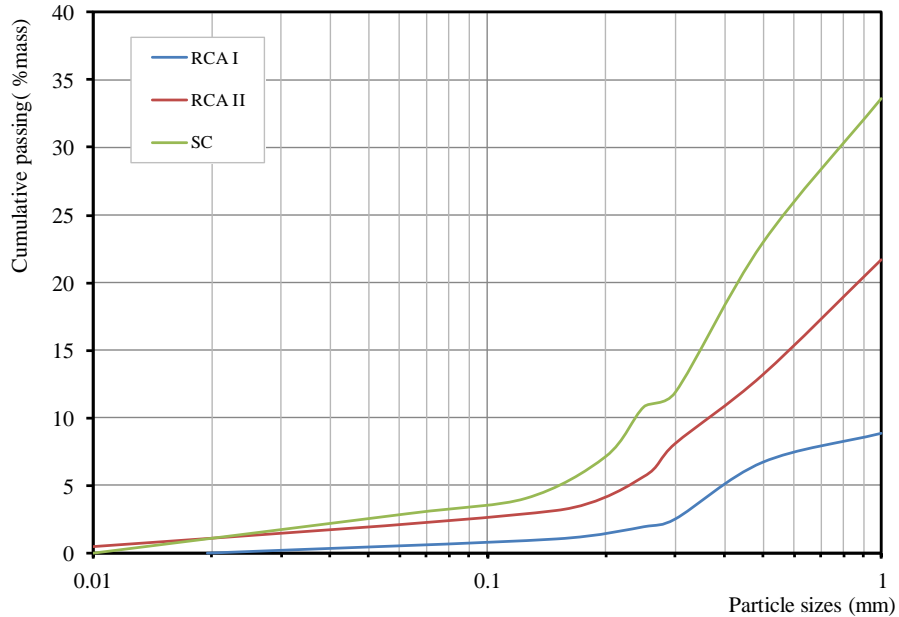


Figure 4.5 PSD of the crushed materials, SC, RCA I and RCA II on a logarithmic scale. Magnification of the PSD under 1 mm.

It is observed from Figure 4.5 that for particles under 0.5 mm, the SC I produced 23% by mass of material, the RCA I produced 6.7% by mass of the total material and the RCA II generated 13.2% by mass. SC I produced about 3 times as much as RCA I and about 2 times as much as RCA II of the particles under 0.5 mm.

The thermal treatment approach is intended to produce the material that can be used to replace cement. It is reasonable to use recycled fines that have particle sizes close to those of cement. Particle sizes of the binder material have to be small in order to achieve a high activity. However, it can be seen from the SC I curve that particles smaller than 125 μm composed only 4.1% by mass of the total recycled material. Particles smaller than 150 μm were selected as the final material used for thermal treatment. One of the reasons is the compromise between the activity of the fines and the amount of material that can be obtained in the laboratory.

4.2.2 Densities of the recycled concrete aggregates

As mentioned before, the principal difference between recycled concrete aggregates and natural aggregates is the attached mortar. 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 densities to that of natural aggregates the less attached mortar they have. 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 the pores in mortar, all the samples were milled into

powder by a ball mill at the same speed for 10 minutes. After that, obtained powders from different recycled concrete aggregate sizes were put in an oven and dried at 70 °C for 24 hours to avoid the influence of moisture. The densities were measured by a pycnometer; the results are presented in Figure 4.6.

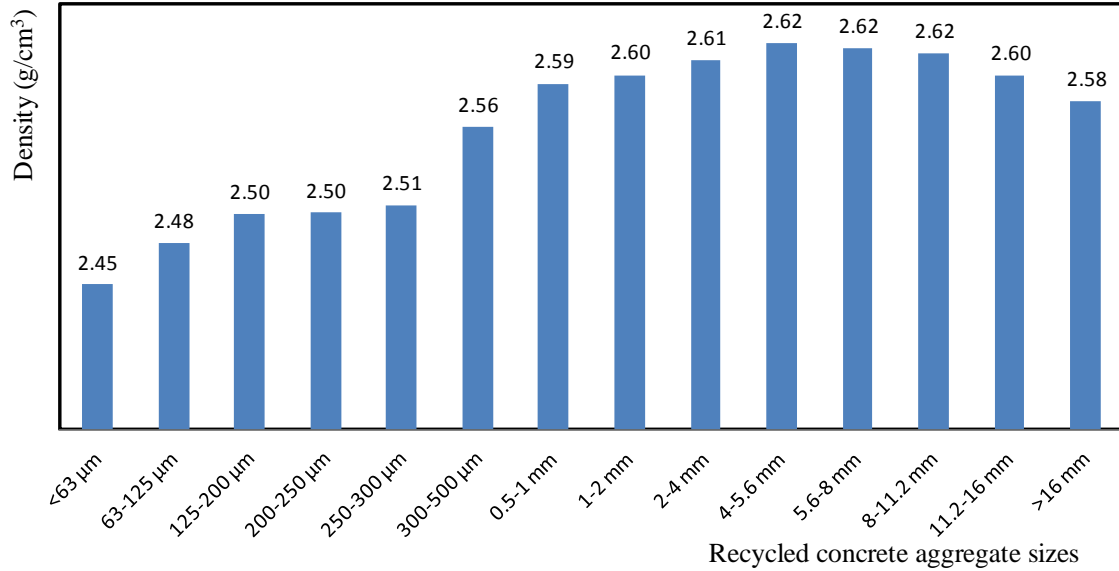


Figure 4.6 Densities of recycled concrete aggregates of different sizes obtained by the smart crusher.

As can be seen from Figure 4.6, particles smaller than 63 µm have the density of 2.45 g/cm³ which is the lowest density among all the recycled materials. The densities have a trend of increasing until particles between 4 mm and 5.6 mm; the densities then stabilize at around 2.62 g/cm³ and decrease when the particles are bigger than 8 mm. As stated before, the D_{max} of the gravel used for the source concrete was 8 mm. Recycled aggregates above 8 mm are considered with large amount of cement paste attached to the surface. The density decrease found for particles bigger than 8 mm can thus be explained.

As stated before, the recycled aggregates are composed of pure cement paste and natural aggregates. It can be reckoned that the lower density of the recycled aggregate means a higher cement paste content. 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 source concrete. The water cement ratio used was 0.7. The pure cement sample was cast in moulds with the dimension of 40 mm × 40 mm × 160 mm and cured under the standard condition for 8 months. Then, the pure cement paste was crushed into small pieces. The α -quartz is from sand, which was shown to be constituted of 98% SiO₂ by XRF measurements. The mixtures of cement paste and sand were blended together with the ratios shown in Table 4.4; then milled into powders and dried. The density result is also shown in Table 4.4.

Table 4.4 Densities of mixtures of pure cement paste and Norm sand

Cement paste (%mass)	Norm 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

From Table 4.4, the speculation of the relationship between the cement paste content and the density is validated. For recycled concrete aggregates, the lower the density, the higher the cement paste content. This is further validated by using the TG-DSC analysis.

4.2.3 TG-DSC analysis of recycled concrete aggregates.

For all the recycled aggregates size fractions, the thermal performances of the powders made for density tests were analyzed by Netzsch STA F1. Figure 4.7 shows the TG-DSC analysis result of recycled particles of 300-500 μm .

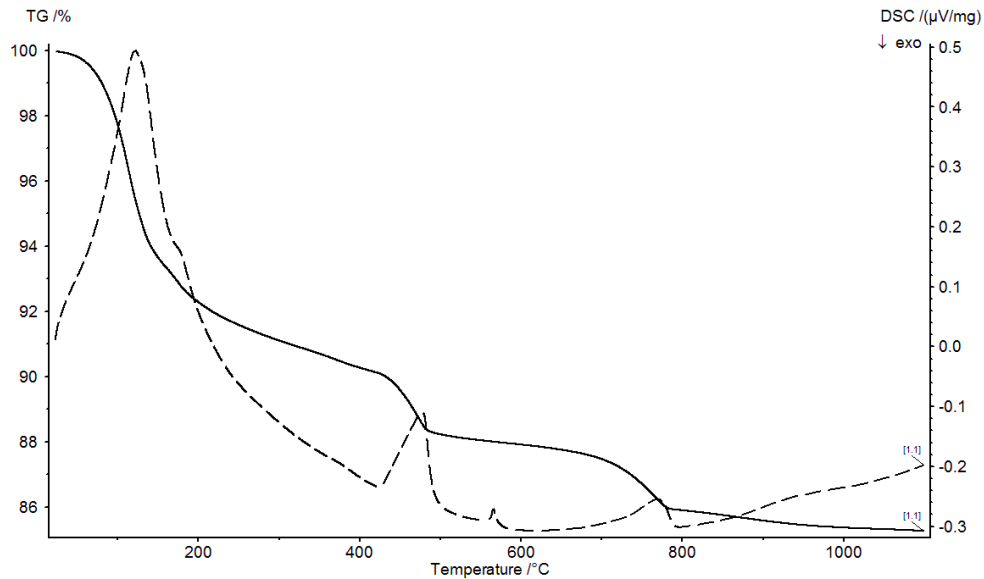


Figure 4.7. TG-DSC analysis of SC I 300-500 μm

It can be seen from Figure 4.7 that the TG curve shows a continuous decrease of the mass of the sample with the increasing of temperature. The mass loss is due to several reasons: the dehydration of C-S-H gel

above 100 °C; the loss of H₂O from the dissociation of portlandite above 450 °C; the decomposition of calcite and generation of CO₂ above 700 °C (Alonso & Fernandes, 2004; Shui et al., 2008).

Table 4.5 Chemical changes of RCF registered by TG curve.

Temperature	Reactions
> 100 °C	C-S-H → Partly dehydrated C-S-H + H ₂ O
> 450 °C	Ca(OH) ₂ → CaO + H ₂ O
> 700 °C	CaCO ₃ → CaO + CO ₂

The corresponding DSC curve registers four major thermal reactions upon heating. The first peak happens between 100 °C and 200 °C, which is mainly due to the evaporation of physically bound water, dehydration and transformation of hydrated products (Alarcon-Ruiz et al., 2005). From the TG curve, it can be seen that there is a major mass loss during this period. The second peak happens between 400 °C and 500 °C along with a weight loss, which can be attributed to the dehydroxylation of calcium hydroxide, which is an endothermic reaction (Alonso & Fernandes, 2004; Shui et al., 2008). The third peak appears at about 570 °C, however, without mass loss recorded by the TG curve. The reason is the transformation of quartz (Shui et al., 2008) which is a phase change process without mass losses. At the temperature around 570 °C, α -quartz transforms into β -quartz with a swell in volume and a decrease in density. The densities of α -quartz and β -quartz are 2.53 g/cm³ and 2.65 g/cm³, respectively. This transformation is instantaneously and reversible, once the temperature of the sample drops below the transformation temperature, β -quartz turns back to α -quartz. The fourth peak of the DSC curve happens between 700 °C and 800 °C, this can be explained by the decarbonation of calcium carbonate and the loss of CO₂; the mass loss is also recorded by the TG curve (Shui et al., 2008).

The TG-DSC curve can also be used to quantify the concentration of the respective compounds within the sample. This can be done by integrating the areas under the related DSC peaks or by computing back from the TG mass losses. The peak areas of the α -quartz were used to determine the quartz content of each recycled concrete aggregates fraction. All the samples prepared for the density test were analyzed by the TG-DSC machine. A calibration curve was also obtained by analyzing mixtures from Table 4.4 with known α -quartz contents. Figure 4.8 shows the calibration curve and the corresponding equation used to compute the α -quartz contents of all considered samples.

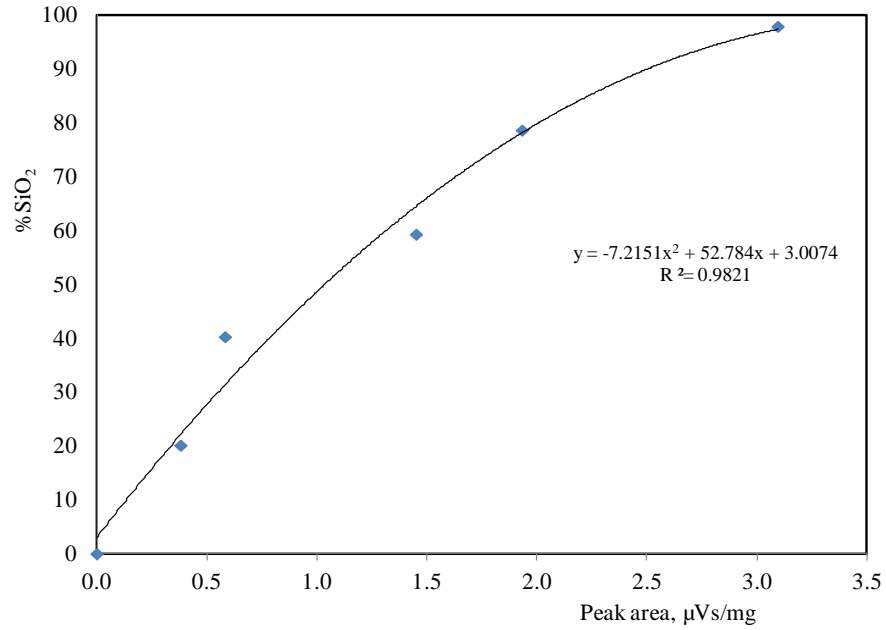


Figure 4.8. Calibration curve for a sand-limestone mixture by using DSC measurements.

The α -quartz contents of all the recycled concrete aggregates from the smart crusher were determined by the above mentioned method and the results are shown in Figure 4.9. The content of the α -quartz aggregates in the concrete mix is 76%, which means that particles above 2 mm are enriched in quartz.

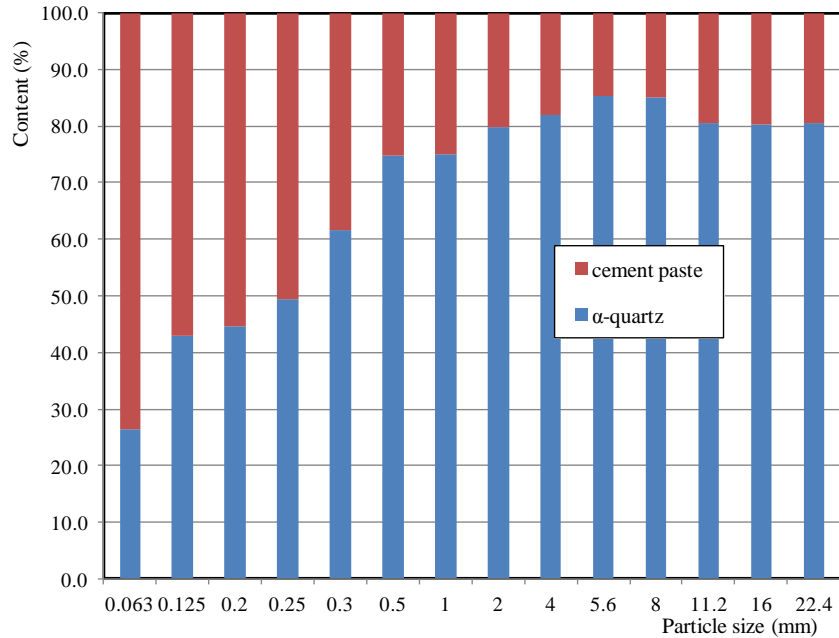


Figure 4.9. α -quartz content in recycled concrete aggregates

It can be seen from Figure 4.9 that particles below 63 μm have the lowest α -quartz content of 26.4% among all the recycled aggregates. The rest 73.6% of the sample is the hardened cement paste. The 63-125 μm fraction contains approximately 42% α -quartz. With the increased sizes, the α -quartz contents keep increasing until the particles between 5.6-8 mm. The recycled aggregate with the highest α -quartz content is found to be the particles between 5.6-8 mm which has 85.3% of α -quartz. The figure also illustrates 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 recycled aggregates produced by the smart crusher that are bigger than 2 mm have more than 80% of α -quartz.

The accuracy of this method is validated by XRF analysis of the same samples. Part of the XRF result is shown in Table 4.6.

Table 4.6 XRF analysis of recycled concrete aggregates.

Particle Size (mm)	CaO (%)	SiO₂ (%)
0-0.063	33.47	39.91
0.063-0.125	26.88	52.10
0.125-0.2	24.26	55.34
0.2-0.25	23.09	57.38

The content of SiO₂ measured by XRF ((SiO₂%)_{XRF}) in recycled concrete aggregates is the sum of α-quartz and SiO₂ from the hydration products. The content of SiO₂ from the hydration products can be traced back from the chemical composition of the cement ((SiO₂%)_{CEM}). The content of α-quartz is measured by the DSC curve ((α-quartz%)_{DSC}) method. The relationship can be expressed as:

$$(\text{SiO}_2\%)_{\text{XRF}} = (\alpha\text{-quartz}\%)_{\text{DSC}} + (1 - (\alpha\text{-quartz}\%)_{\text{DSC}}) * ((\text{SiO}_2\%)_{\text{CEM}}) \quad (4.1)$$

To take RCF particles smaller than 63 μm as an example, the SiO₂ measured by XRF is 39.91%. The α-quartz content determined by TG-DSC is 26.4%, which means the hydration products has the percentage by weight of 73.6%. As is known that, ENCI CEM I 42.5 N has the SiO₂ content of 20.0%, the SiO₂ from hydration products is 14.72%. Therefore, the total SiO₂ determined by TG-DSC method is 41.12%, the error between the XRF result and the TG-DSC method is only 1.21%.

The TG-DSC method can also be used to determine the amounts of calcium hydroxide and calcium carbonate in recycled concrete aggregates. Take the TG graph in Figure 4.7 as an example, the portlandite is calculated to be about 8.2% and calcite is calculated to be about 4.5%.

It is also found the densities have a correlation with the α-quartz contents. Figure 4.10 shows the density of the samples (right y-axis) on the same graph with the SiO₂ contents (left y-axis).

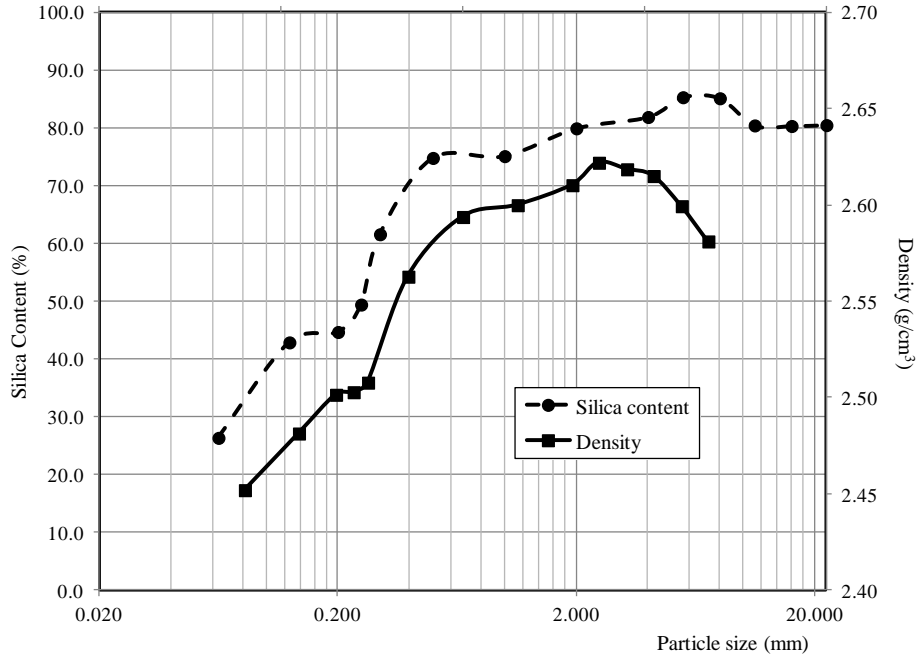


Figure 4.10 Density (g/cm^3) and α -quartz content (%) of recycled concrete aggregates

Figure 4.10 shows a good agreement between the density and α -quartz content of the recycled concrete aggregates. This suggests that density measurements can be used for the recycled concrete aggregates α -quartz content estimation.

4.3 Thermal treatment of recycled concrete fines

4.3.1 Fractioning the materials

Based on the silica content, the particle size and the amount of material that can be obtained from the source concrete, the material used for thermal treatment was selected as the recycled concrete fines (RCF) under $150 \mu\text{m}$. The selected RCF have a hardened cement paste content of approximately 57%, the rest being α -quartz.

4.3.2 Thermal treatment program

Based on the TG-DSC study, the thermal treatment temperatures for recycled concrete fines were selected at $500 \text{ }^\circ\text{C}$, $800 \text{ }^\circ\text{C}$ and $1100 \text{ }^\circ\text{C}$. The selected temperatures are slightly higher than the major phase changes of compounds within the fines.

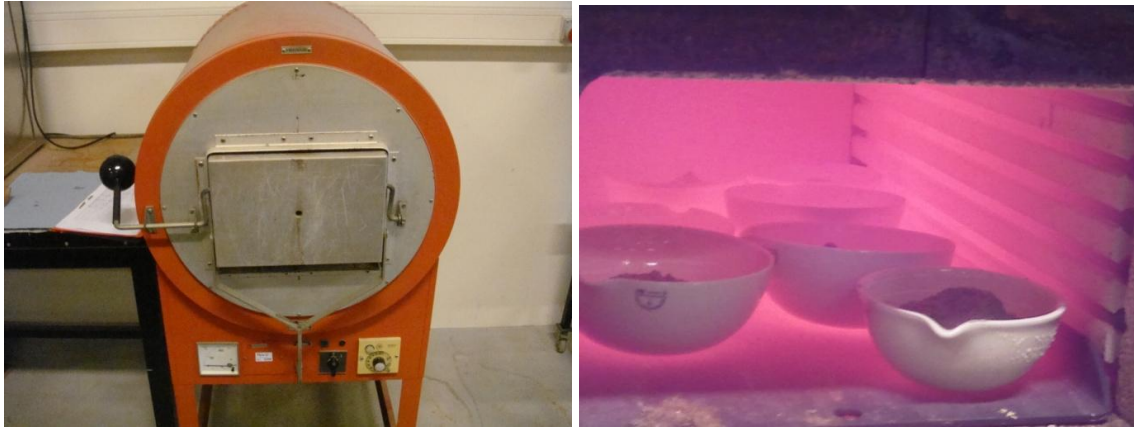


Figure 4.11 The oven used for thermal treatment (left) and the materials during the thermal treatment (right)

The fines were placed in ceramic bowls and kept in the heating regime for overnight (16 hours) then turn off the oven with the door open for 2 hours. The fines were then kept in open air (1 hours) until the fines were cooled down to the room temperature. Once the thermal treatment was finished, the thermally treated fines were sealed in plastic bags and kept for further tests.

4.3.3 Chemical composition and PSD of all the binders used in this study

In this research, binders are considered to be the materials that can build up strength; materials that show cementitious or pozzolanic properties are considered as binders. The binders used in this research are ENCI CEM I 42.5N, RCF, paper sludge fly ash, PKVA SMZ fly ash and ORCEM slag. The chemical compositions of all the materials are presented in Table 4.7.

Table 4.7 Chemical composition of the binder materials used in this research

Oxide	ENCI CEM I 42.5N	RCF < 150 μm	Paper sludge fly ash	PKVA SMZ	ORCEM Slag
Al_2O_3	5.0	3.0	15.0	22.3	12.6
SiO_2	20.0	52.0	22.0	55.0	35.0
SO_3	2.2	<1.0	1.0	1.4	0.1
CaO	63.0	36.0	57.0	4.4	39.2
Fe_2O_3	3.0	2.0	0.7	8.4	0.4
MgO	1.6	0.85	2.0	1.9	8.9
LOI	1.1	N/A	N/A	N/A	1.3

In Table 4.7, the chemical composition of RCF can be found. It has the CaO content of 36% and the SiO₂ content of 52% of which about 43% is α -quartz. Paper sludge fly ash has a similar chemical composition as cement, there is 57% CaO. However, the CaO existing in paper sludge fly ash is in the form of CaCO₃, which can not contribute to the strength development. PKVA SMZ is a low lime commercial fly ash available on the Dutch market; it can be categorized as Class F fly ash by American Society for Testing and Materials (ASTM) standard ASTM C618. In the Netherlands, more than 50% of the cement delivered to the market is CEM III which is made from slag and cement clinker (Wei, 2006). ORCEM Slag has a calcium oxide content of 39.2% and 98% of its SiO₂ being in glassy state.

The used binder materials were measured by Mastersizer 2000; the particle size distributions are presented in Figure 4.12. “Untreated fines” are RCF under 150 μm without thermal treatment; 500 $^{\circ}\text{C}$, 800 $^{\circ}\text{C}$ and 1100 $^{\circ}\text{C}$ stand for RCF under 150 μm thermally treated at the corresponding temperatures. 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 90% of the material) of all the investigated materials are presented in Table 4.8.

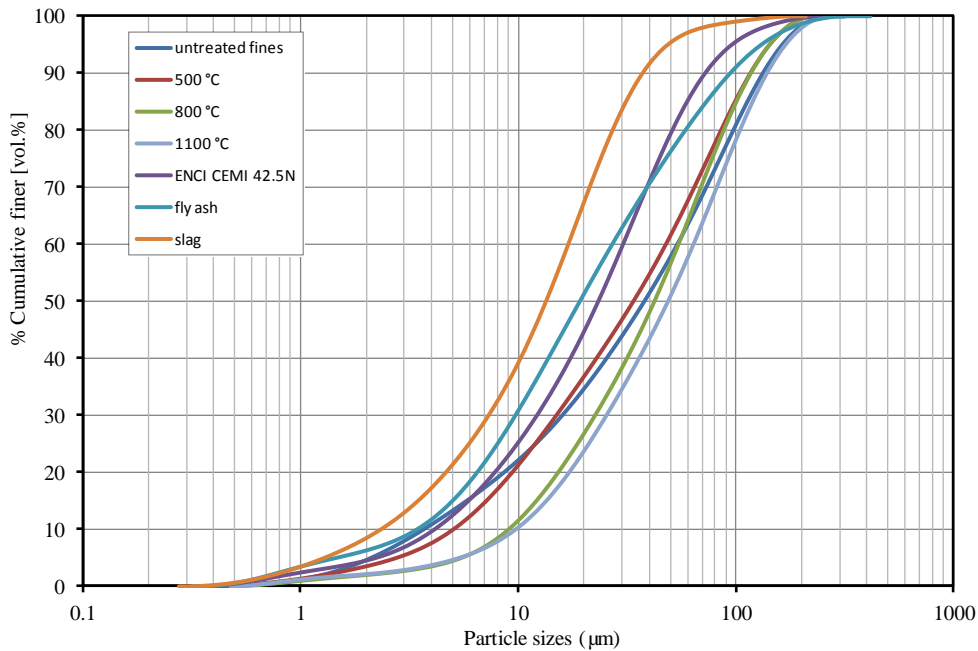


Figure 4.12. Particle size distributions of the binder materials on a logarithmic scale.

Table 4.8 $d_{0.1}$, $d_{0.5}$ and $d_{0.9}$ measured for the binder materials

	$d_{0.1}$ [μm]	$d_{0.5}$ [μm]	$d_{0.9}$ [μm]
Untreated RCF	3.7	38.2	133.8
500 °C treated RCF	5.0	33.9	117.2
800 °C treated RCF	9.1	42.5	118.0
1100 °C treated RCF	9.8	49.1	139.6
ENCI CEM I 42.5 N	4.1	23.4	72.6
Fly ash	3.4	19.2	94.3
Slag	2.3	13.4	37.1

It can be seen from Figure 4.12 and Table 4.8 that the ORCEM slag has the finest particle sizes among all the binder materials, with the corresponding $d_{0.5}$ value of 13.4 μm and $d_{0.9}$ of 37.1 μm . CEM I 42.5 N and PKVA SMZ fly ash have particle sizes close to each other and larger than the ORCEM slag. RCF has the largest particles; moreover, thermal treatment has the effect of clumping small RCF particles together. This can be seen more significantly from the PSD curves of 800 °C treated and 1100 °C treated RCFs.

4.3.4 Physical, and mineralogical changes of RCFs exposed to high temperatures

The most significant physical change measured is the change of RCF densities. The densities of the RCF treated at different temperatures were measured by a pycnometer. The results are presented in Table 4.9.

Table 4.9 Densities of the original and thermally treated RCF

	Density (g/cm^3)
Untreated RCF	2.52
500 °C treated RCF	2.65
800 °C treated RCF	2.92
1100 °C treated RCF	2.89

As can be seen from Table 4.9, the densities of the RCF increase along with the elevated thermal treatment temperature until 800 °C. This is due to the losing of physically and chemically bounded water during the thermal treatment procedure, this leads to the increase of the densities of RCF.

The recycled fines had a series of chemical and physical changes after thermal treatment; these can be called mineralogical changes. X-ray Diffraction was used to identify the crystalline phases in the untreated fines and dehydrated phases in the thermally treated fines. In this case, the untreated fines were considered as the reference for identifying the phase changes in the thermally treated fines. The XRD patterns of the reference, RCF treated at 500 °C and 800 °C are illustrated in Figure 4.13, where the main crystalline phases were identified and marked with specific symbols.

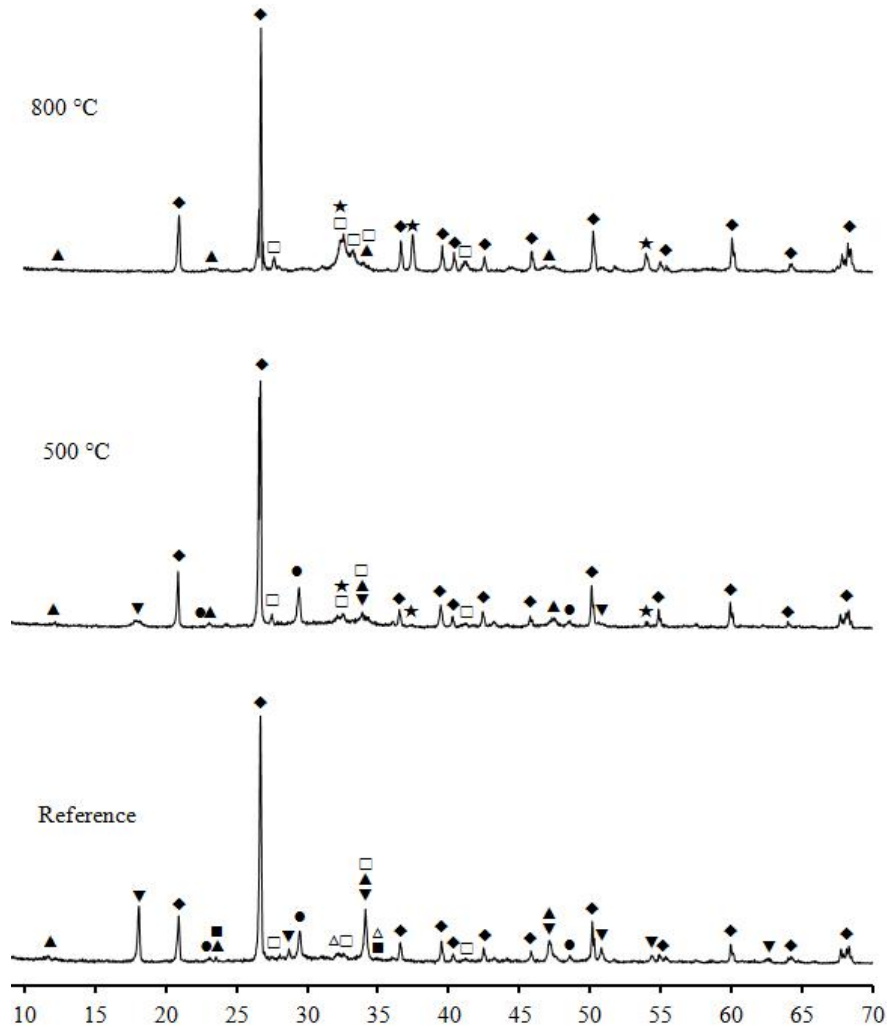


Figure 4.13. XRD of reference RCF and thermally treated RCF at 500 °C and 800 °C. Note: α -Quartz (◆); C_2S (□); Portlandite (▼); Calcite (●); Brownmillerite (▲); Ettringite (■); C-S-H (Δ); Lime (★).

In Figure 4.13, the typical reflections associated to α -quartz (S), larnite (C_2S), portlandite (CH), brownmillerite (C_4AF), calcite ($CaCO_3$), ettringite ($C_6A\bar{S}_3H_{36}$) and C-S-H were found in the reference sample. In the 500 °C treated sample, the significant difference from the reference are the reduction of the peak of portlandite, the disappearance of ettringite and C-S-H gel. When this phenomena is associated with the TG-DSC analysis, it can be proven that the portlandite transforms to CaO and H_2O during this

period. Another evidence is the appearance of lime in the 500 °C treated sample. In the 800 °C treated pattern, the presence of lime is detected and increases its intensity more than in the 500 °C pattern. However, calcite disappears between the temperature of 500 °C and 800 °C. This can be explained by the dissociation of calcite at the temperature of around 750 °C. Portlandite no longer exists in the 800 °C treated sample. The occurring reactions were presented in Table 4.5. The brownmillerite and larnite are present in all the measured samples, α -quartz is present in all the samples and has the highest intensities in all samples. This is due to the relatively large fraction of sand in RCF. The transition from α -quartz to β -quartz is immediate and reversible. The structural change happens instantaneously at normal pressure as soon as the temperature of 573 °C is reached. The reason that there was no β -quartz present in the 800 °C treated sample was that all the samples were measured by the XRD machine when they were cooled down to the room temperature, allowing the transition of β -quartz back to α -quartz.

The experimental results also validate some other research results from Shui (2008) and Alonso (2004). In combination with the result of TG-DSC, conclusions can be made for the effect of thermal treatment on the transformation of the phases existing in RCF. The ettringite and C-S-H gel dehydrate between room temperature and 500 °C. Portlandite loses a water molecule at the temperature of about 450 °C; however it is not completely dissociated until 500 °C. Calcite, dissociates at the temperature around 750 °C; the transformation finishes completely at 800 °C. Free lime is obtained at 500 °C and increases its intensity up to 800 °C.

4.3.5 Scanning electron microscopy (SEM) and energy dispersive X- Ray (EDX) study

The microstructure of the hydrated cement paste and the morphological characteristics of RCFs treated at different temperatures were investigated by scanning electron microscopy (SEM). The energy dispersive X-Ray (EDX) was employed for the elemental analysis of the RCF. The microstructure of the 28 days cement hydration products is shown in Figure 4.14

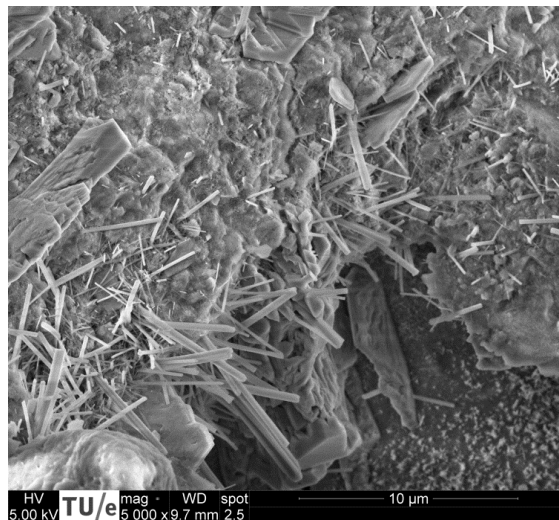


Figure 4.14 SEM image of hardened cement paste at the magnification of 5000 times.

The hydration products can be observed from Figure 4.14: needle like ettringite, blocky plates of CH and C-S-H gel that is filled in the rest of the space. C-S-H gel account for the main strength of concrete, CH can contribute little to the concrete strength (Wang, Baxter, & Fonseca, 2008).

The RCF, without thermal treatment, is investigated by both SEM and EDX. The obtained images are presented in Figure 4.15.

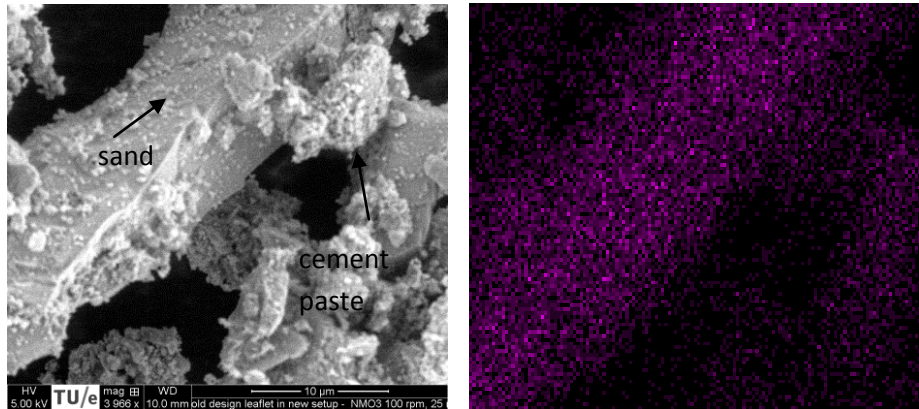


Figure 4.15 SEM image of a RCF particle (left) and its silicon map from EDX (right)

It can be clearly seen from Figure 4.15 (left image) that a sand grain with cement paste attached to its surface. The EDX image (right) of silicon was taken for the same particle grain which clearly verified that the surface of the sand is covered with silicon element, this is because the sand is mainly composed of SiO_2 . Thermally treated RCFs are also investigated by SEM. The images are presented in Figure 4.16.

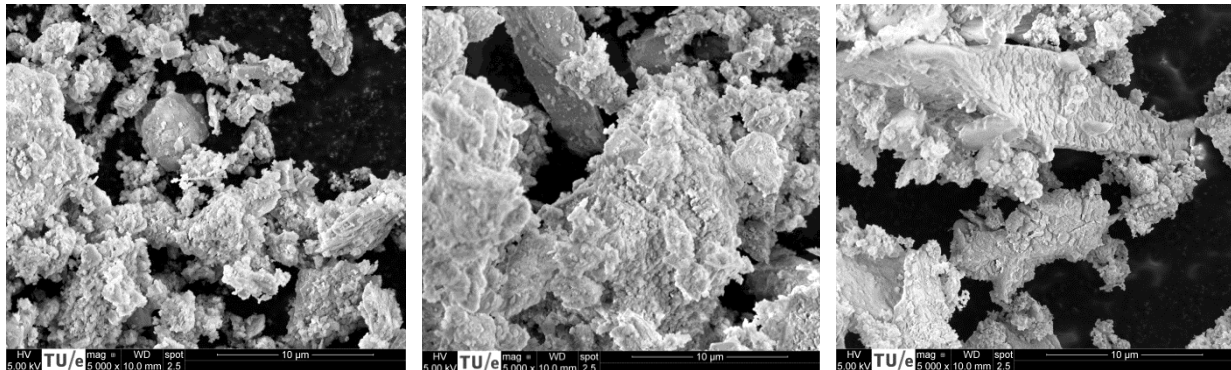


Figure 4.16 SEM images of untreated RCF, 500 °C treated RCF and 800 °C treated RCF at the magnification of 5000 times.

C-S-H gel or dehydrated C-S-H can be observed from all the three samples. In Figure 4.16 left, Portlandite can be found, however, needle like ettringite is missing. The reason that the ettringite is not shown in the SEM image of the untreated RCF still has to be further investigated. In the SEM images of 500 °C treated RCF and 800 °C treated RCF, sand and dehydrated cement paste can be seen.

4.3.6 Calorimetry study of the recycled concrete fines

The rehydration heat of the thermally treated RCF was measured by a calorimeter. The recipe is presented in Table 4.10, in which, RCF 20 stands for the untreated RCF; RCF 500 stands for the 500 °C treated RCF; RCF 800 stands for the 800 °C treated RCF. RCF 800 has the highest water demand, a water/RCF ratio of 0.9 was used.

Table 4.10 Calorimetry recipe of RCF

	water/RCF	Water (g)	RCF (g)
RCF 20	0.7	7	10
RCF 500	0.7	7	10
RCF 800	0.9	9	10

The obtained calorimetric curves are presented in Figure 4.17

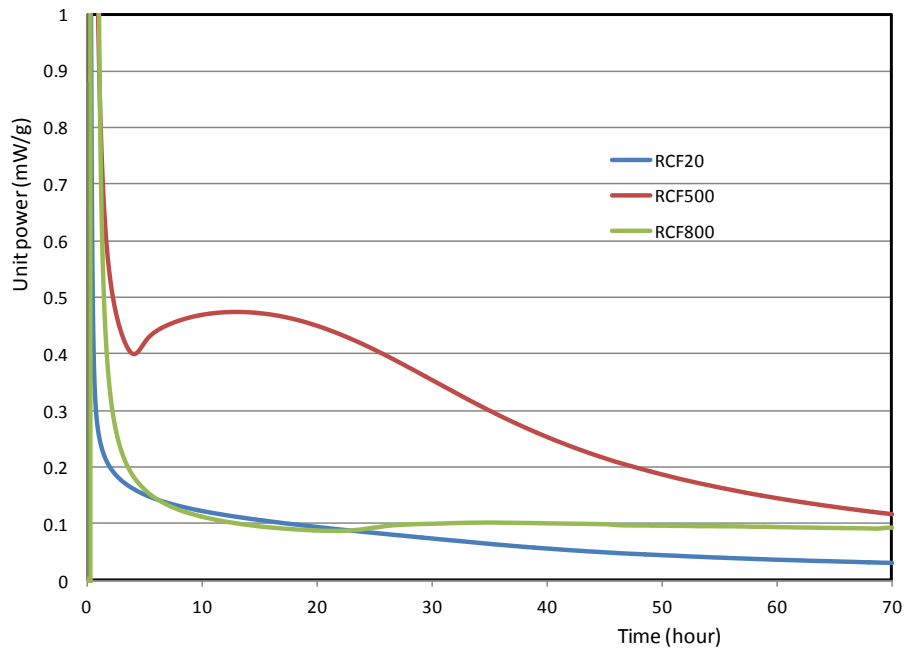


Figure 4.17 Calorimetric curves of RCF

The total heat released per gram of RCF are presented in Table 4.11. In the case of thermally treated RCF, due to the presence of CaO, reacts with water quickly, the first 45 minutes of heat generation is also presented in Table 4.11.

Table 4.11 Total heat released per gram of RCF for the first 45 minutes and 70 hours.

	45 min (J/g)	70 hour (J/g)
RCF 20	5.50	24.27
RCF 500	11.88	88.79
RCF 800	19.62	48.48

As can be seen from Figure 4.17, RCF 500 has the highest heat liberation rate during the first 70 hours with a rehydration peak that can be clearly seen. RCF 20 has a decreasing heat generation rate, the heat at the beginning part is probably generated by the unhydrated cement. RCF 800 has an unnoticeable peak after about 24 hours. The heat generation of the first 45 minutes can be seen from Table 4.11 that the hydration heat increases with increasing thermal treatment temperature, with RCF 800 the highest. This is due to the quick reaction of the free lime in the RCF treated with high temperature; RCF 800 has the highest lime content. The RCF 500 has the highest 70 hour heat generation per gram, which is 88.79 J/g. RCF 20 has the lowest heat generation of 24.27 J/g. RCF 800 generates higher heat than RCF 20, however, is much lower than RCF 500. The reason that the hydration heat of the RCF 800 is lower than that of RCF 500 has to be further investigated.

4.4 RCF replacement tests

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 4.12. RCF treated with different temperatures were used to replace part of the cement in the standard mortar sample.

4.4.1 OPC replacement test

Untreated RCF, 500 °C treated RCF and 800 °C treated RCF (description of treatment in section 4.3.2) were used to replace 10%, 20% and 30% of cement in the standard mortar sample. PKVA fly ash 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 4.12. The term replacement material in Table 4.12 means untreated RCF, 500 °C treated RCF, 800 °C treated RCF or PKVA fly ash.

Table 4.12. 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 consistence of the fresh mortar samples was determined by using the flow table test according to EN 1015-3 as described in Chapter 3.6.1. Original and thermally treated RCFs have higher water absorption than that of cement. In order to obtain similar spread as the reference mortar, superplasticizer was used for the RCF 20% replacement and 30% replacement samples. The technical information and the dosages of the superplasticizer are shown in Table 4.13.

Table 4.13 Technical information of the superplasticizer

Name	Glenium 51
Density (g/ml)	1.1
Concentration (%)	30.0
pH-value	7.0 ± 1.0
Dosage (mass%) for RCF 10% replacement	0
Dosage (mass%) for RCF 20% replacement	0.12%
Dosage (mass%) for RCF 30% replacement	0.24%

The data depicted in Figure 4.87 show the spread of the mortar samples depending on the RCF content.

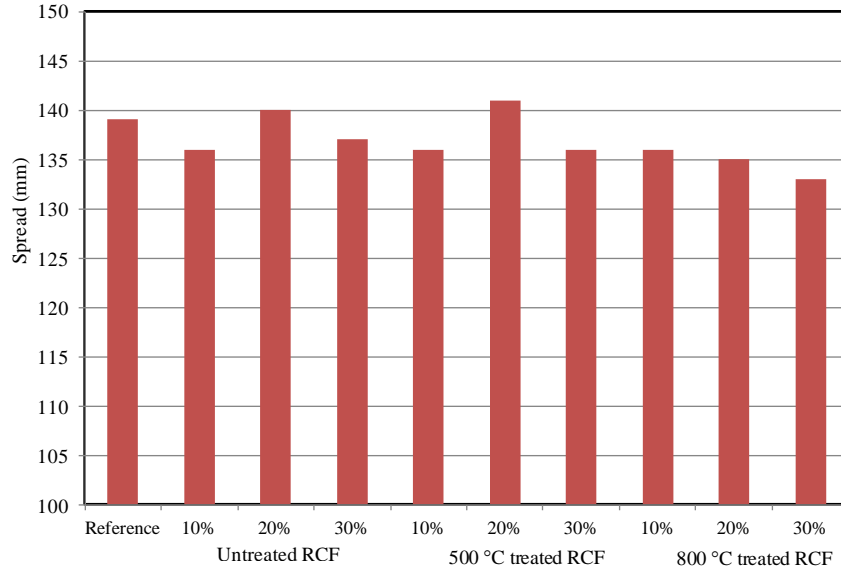


Figure 4.18 Spread of fresh mortars with RCF containing SP.

It can be seen from Figure 4.18 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 Figures 4.19, 4.20, 4.21 and 4.22.

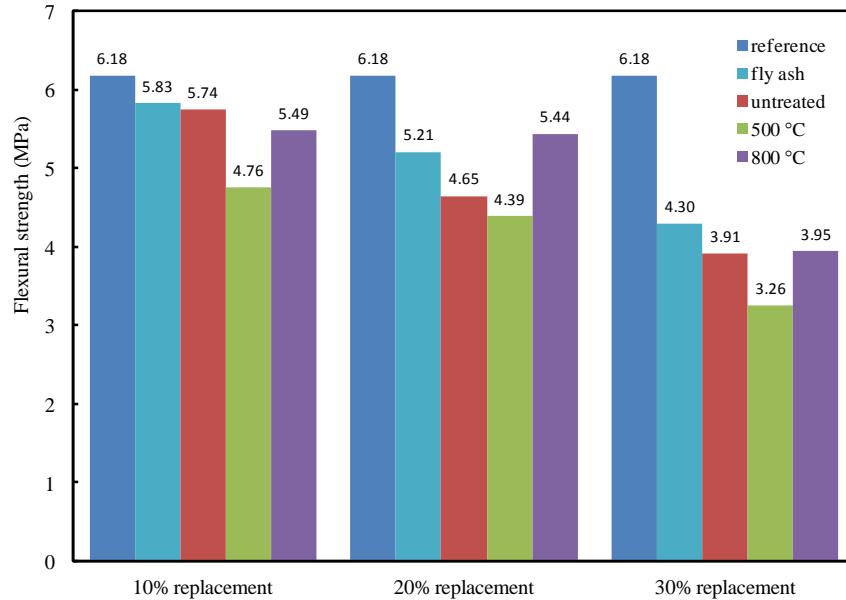


Figure 4.19 7 days flexural strength of RCFs at different replacement ratios.

It is observed from Figure 4.19 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 reduces the flexural strength for all the mortars significantly.

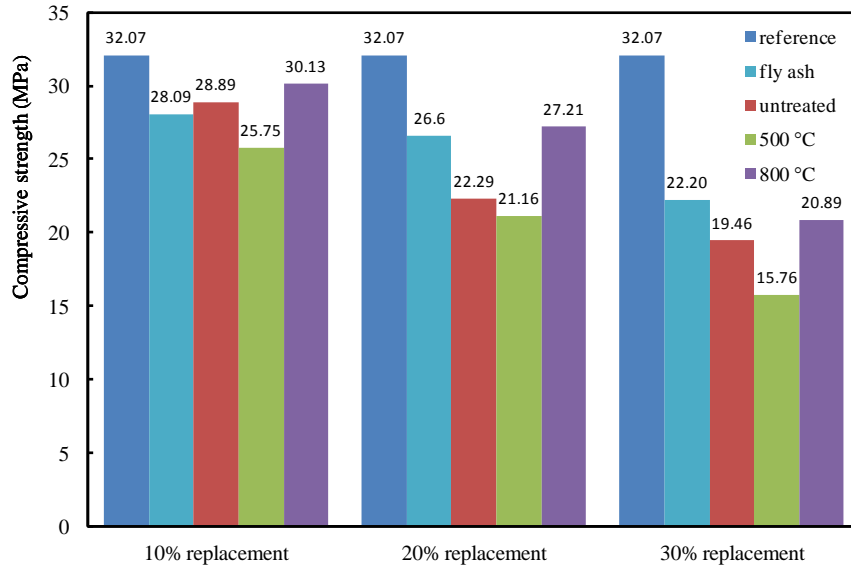


Figure 4.20 7 days compressive strength of RCFs at different replacement ratios.

As can be seen from Figure 4.20, 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.

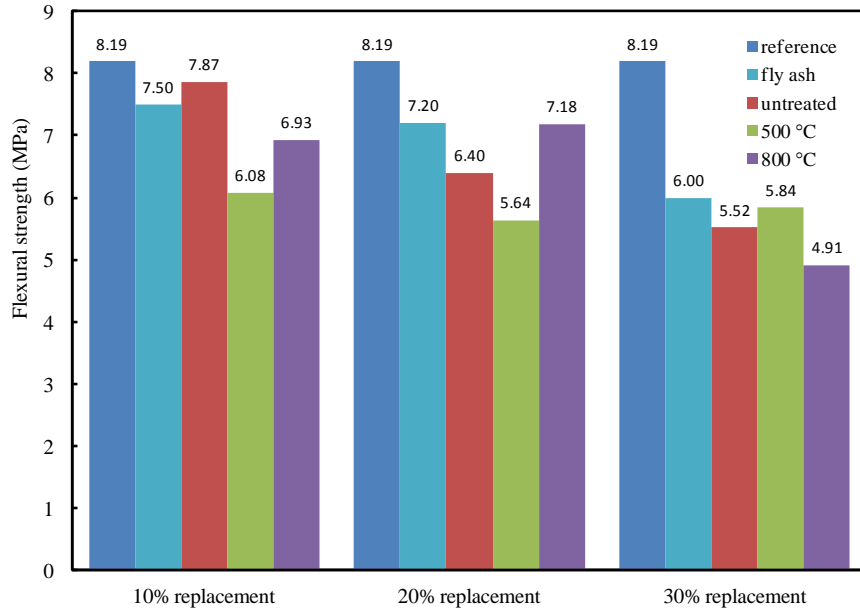


Figure 4.21 28 days flexural strength of RCFs at different replacement ratios.

As can be seen from Figure 4.21, 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 MPa 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.

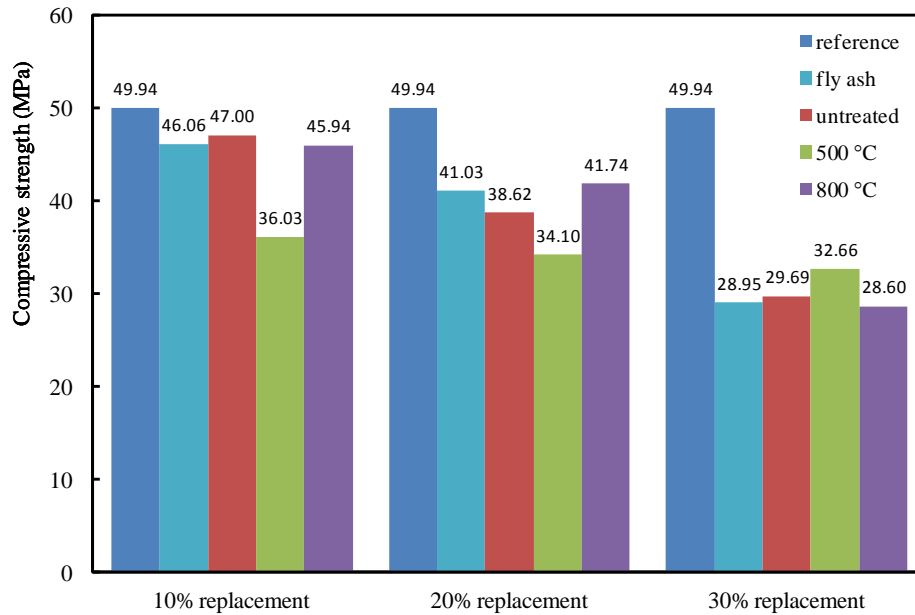


Figure 4.22 28 days compressive strength of RCFs at different replacement ratios.

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 aluminates 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 in contact with water again, the treated phases can no longer recover to the original hydration products.

4.4.2 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 SiO₂ and Ca(OH)₂ (Illston & Domone, 2001).



Slag has a certain level of self cementing ability because of the existence of lime and glassy SiO₂ 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 4.14, the chemical compositions of the binder materials are presented in Table 4.7.

Table 4.14 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 4.23.

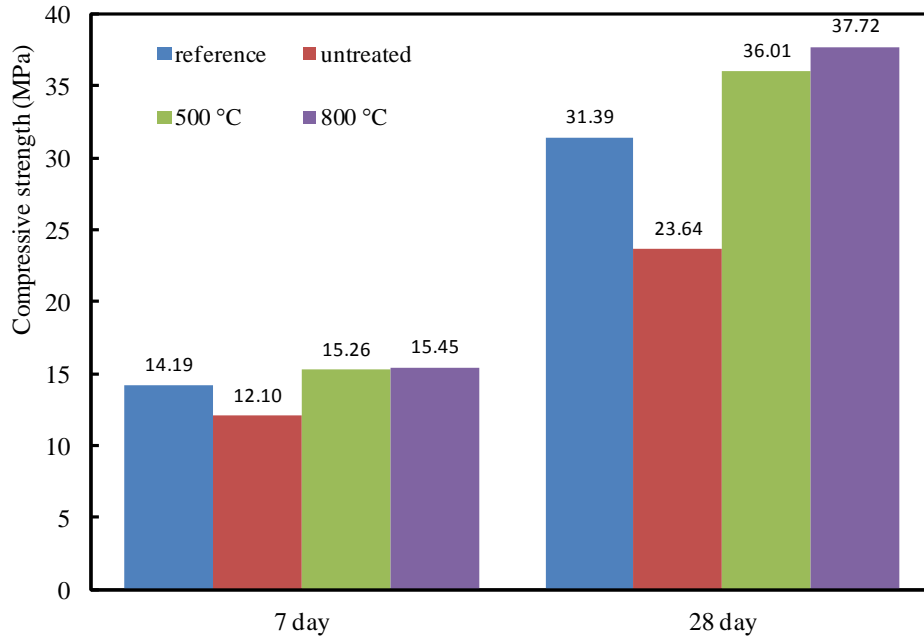


Figure 4.23 7 days and 28 days compressive strength of slag blended cement mortars.

It can be seen from Figure 4.23 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, containing free lime, 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, containing free lime, 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.

4.4.3 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.

Table 4.15 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

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.

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 4.24 and Figure 4.25.

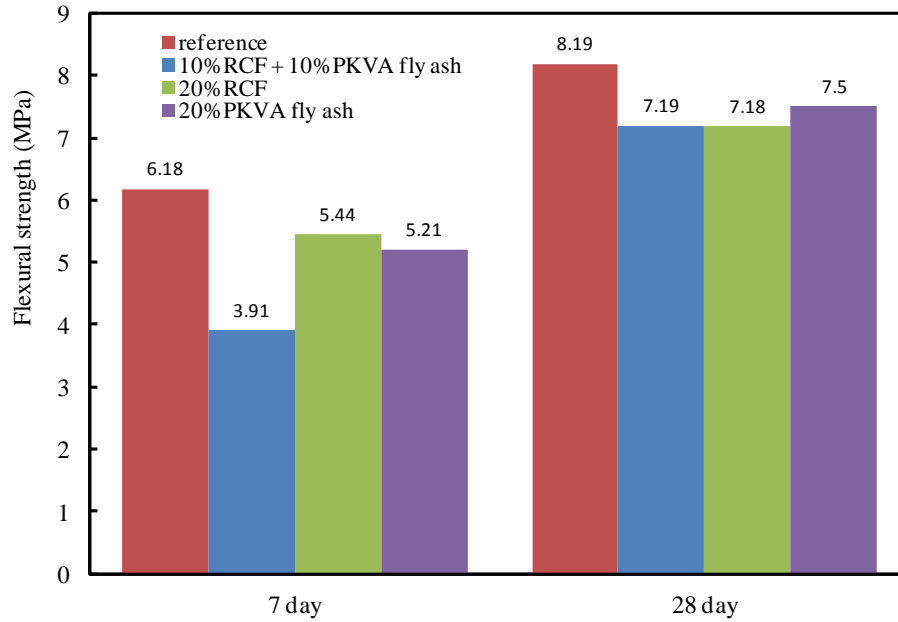


Figure 4.24 7 days and 28 days flexural strength of the reference, 10% 800 °C treated RCF+10% PKVA fly, 20% 800 °C treated RCF and 20% PKVA fly ash replacement mortars.

It can be seen from Figure 4.24 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 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.

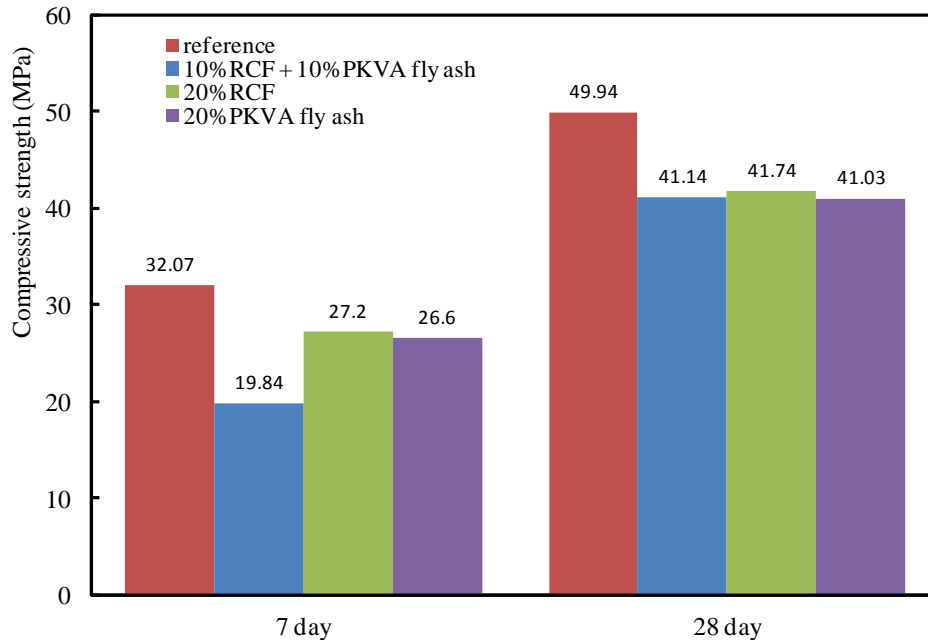


Figure 4.25 7 days and 28 days compressive strength of the reference, 10% 800 °C treated RCF+10% PKVA fly, 20% 800 °C treated RCF and 20% PKVA fly ash replacement mortars.

It is illustrated in Figure 4.25 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.

4.5 RCS replacement test

Recycled concrete sand (RCS) with particle sizes up to 2 mm was used to replace EN 196-1 Norm sand. At the beginning, two bags of Norm sand were sieved; the average value of weight obtained by each sieve was used as the particle size distribution of the Norm sand. RCS, by the same particle size distribution, was used to replace 100% Norm sand. The original weight of the Norm sand was 1350 grams; there was a mass loss of the Norm sand during the sieving process, the weight of the RCS was manipulated to be the same as a new bag. The average value of the sieved Norm sand and the mass of the used corresponding RCS are presented in Table 4.16. The mix proportioning of the tested mortars is given in Table 4.17.

Table 4.16 Sieving of Norm sand and the mass proportioning of 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

Table 4.17 Mix proportioning of tested mortars used for sand replacement by recycled concrete sand.

Material	Reference (g)	RCS (g)
Norm sand	1350	0
RCS	0	1350
CEM I 42.5 N	450	450
Water	225	225

4.5.1 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% by mass of superplasticizer (SP) mentioned in Table 4.13 was added to the mortar mixture. Figure 4.26 illustrates the flow table test of the RCS replacement mortar samples.



Figure 4.26 RCS mortar samples without SP (left) and with SP (right)

As can be seen from Figure 4.26, RCS mortar sample without SP was too dry to flow, it was collapsed instead of spreading to a cake shape. With 1% by mass of SP, the mortar sample had a flow table spread value of 123 mm, this is still lower than the reference mortar of 139 mm.

4.5.2 Strength

The obtained 3 days, 7 days and 28 days flexural and compressive strengths are presented in Figures 4.27 and 4.28.

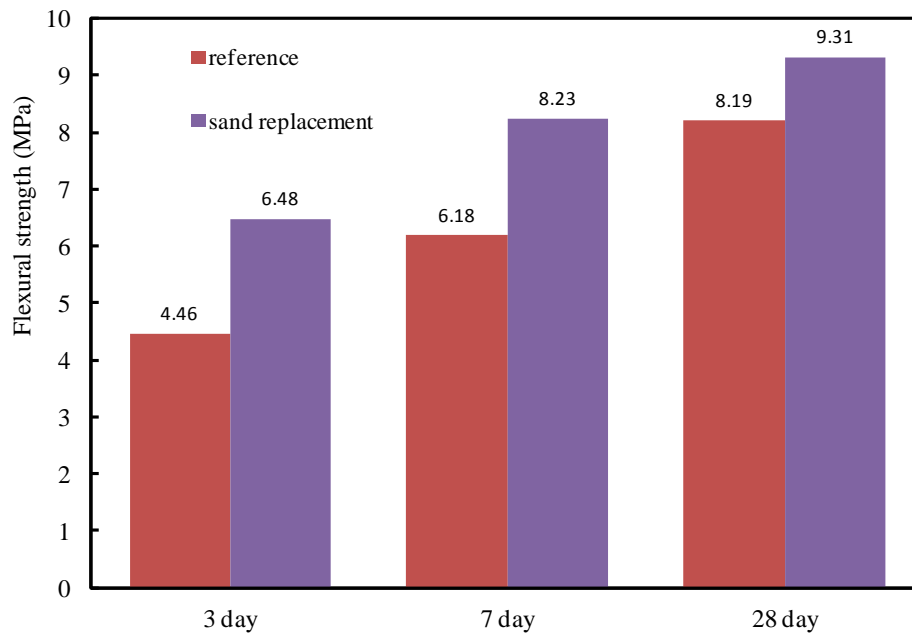


Figure 4.27 Flexural strength of sand replacement mortar

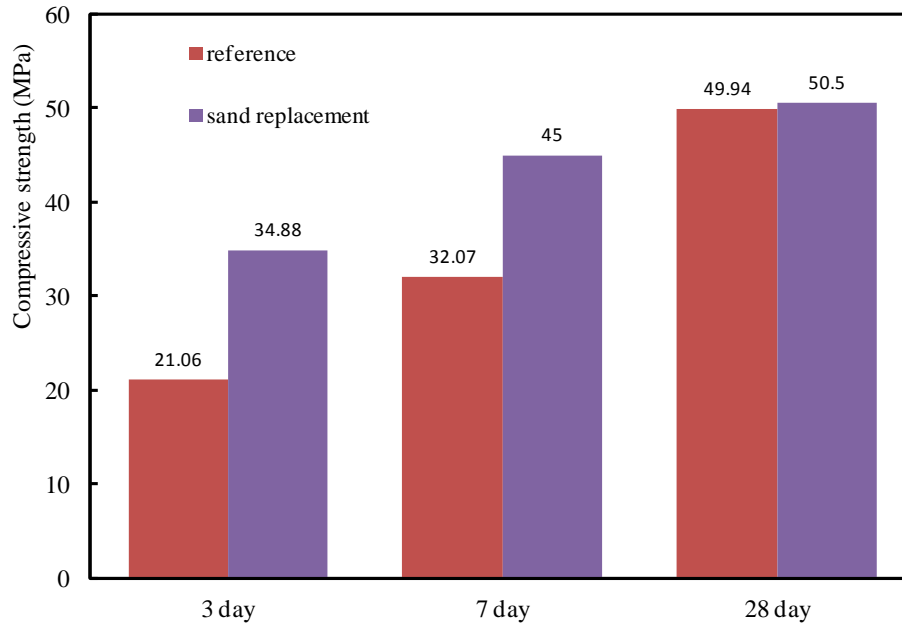


Figure 4.28 Compressive strength of sand replacement mortar

It can be seen from Figure 4.27 and Figure 4.28 that replacing 100% of Norm sand by recycled concrete sand increases the mortar sample strength. For the flexural strength, 3 days strength increased by 45.3%, 7 days strength increased by 33.2% and 28 days strength increased by 13.7%. As for the compressive strength, 3 days strength increased by 65.6%, 7 days strength increased by 40.3% and the 28 days 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 by using 1% by mass of superplasticizer can increase the mortar strength. The RCS mortar has much higher early strength than the Norm sand mortar, especially for the 3 days strength and 7 days strength.

As for the 3 days strength, the RCS mortar 3 days flexural strength reaches 69.6% of its 28 days value; the RCS mortar 3 days compressive strength reaches 69.1% of its 28 days strength. While for the Norm sand mortar sample, the values are 54.5% and 42.1% correspondingly. It can be concluded that by using the RCS to replace 100% of Norm sand along with 1% by mass of superplasticizer can speed up the mortar strength development.

Moreover, RCS has lower density than Norm sand, by using the same weight of RCS means the bigger volume of RCS is used in the mortar sample. Which means the same volume of RCS mortar contains less cement than the Norm sand mortar. Another conclusion can be made that by using RCS together with superplasticizer to replace Norm sand in standard mortar can achieve the same strength with less cement.

However, one thing to be noticed was that the mortar sample made from RCS set much faster than the reference mortar. This was because of the water was absorbed by the RCS which decreases the fresh mortar consistence. RCS can be applied in mass concrete production such as earth moist concrete (Hüsken, 2010).

5 Conclusions and discussions

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 CO₂ 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.

5.1 Conclusions

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. 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 α -quartz content there is. It is also found that the density of the RCA has a correlation with the α -quartz content: low density means a relatively low α -quartz content. As for the thermal treatment, it is preferred to have the RCF that are small in size. Particles under 150 μm 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. α -quartz has the phase transformation at the temperature of about 573 °C and is recovered to α -quartz again when cooled down to room temperature.

It was demonstrated in this thesis 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 significant 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 10% of 500 °C treated RCF and 800 °C treated RCF can increase the 28 days compressive strength of slag and cement 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.

Finally, recycled concrete sand was tested to replace 100% of the Norm sand in the standard mortar sample. Significant decrease of fresh mortar spread was observed; with 1% by mass superplasticizer, the mortar sample obtained a satisfactory flow table spread value. 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%.

5.2 Discussions

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

1. 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.
2. In this research, the 28 days strength were used to compare the effect of the RCF influence of the mortar mechanical performance. It will be more interesting to test the 90 days strength, especially when comparing with fly ash.
3. 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 thesis, the smaller sized RCF has significantly lower amounts of α -quartz, which is considered as inert. It is speculated that better results can be obtained if particles under 63 μm can be used instead of the 150 μm RCF, because RCF with small particles sizes also have more contact surface with water during hydration.
4. Thermally treated RCF will lower the mortar sample fresh properties; superplasticizer can be used to compensate this effect. It is also interesting to see whether a retarding admixture can be used to elongate the fresh mortar setting time. Thermally treated RCF, if used to replace higher than 30% of cement, can possibly be used for plaster engineering which has lower requirement in terms of strength than structural use.
5. 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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