C2CA Concrete Recycling Process
From Development To Demonstration

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C2CA Concrete Recycling Process

From Development To Demonstration

Somayeh Lotfi

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C2CA Concrete Recycling Process:
From Development To Demonstration

Proefschrift

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To my beloved parents and husband

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CHAPTER 1

Introduction

1.1 GENERAL

Production of waste materials, via industrial and human activities, creates big environmental and economic problems but also opportunities to recover valuable resources. Thus, the management and treatment of industrial solid waste and municipal waste has recently got more attention worldwide. This waste can be relatively inert, e.g. glass bottles, excavated soil, construction and demolition waste, or can be hazardous waste with high concentrations of heavy metals and toxic organic compounds. Statistics show that each European Union citizen produced, on average, about 5.2 tonnes of waste in 2008 [1]. Figure 1-1, shows the mass percentage of different waste categories generated in EU-28 in 2012 [2]. The figure indicates that the construction sector is the main producer of the EU waste in terms of mass. Worldwide, building materials account for about half of all materials used and about half of the solid waste generated in terms of mass. In spite of the potential resources existing in such wastes, until recently the Construction and Demolition Waste (CDW) stream has not got great attention in comparison with other waste streams[3].

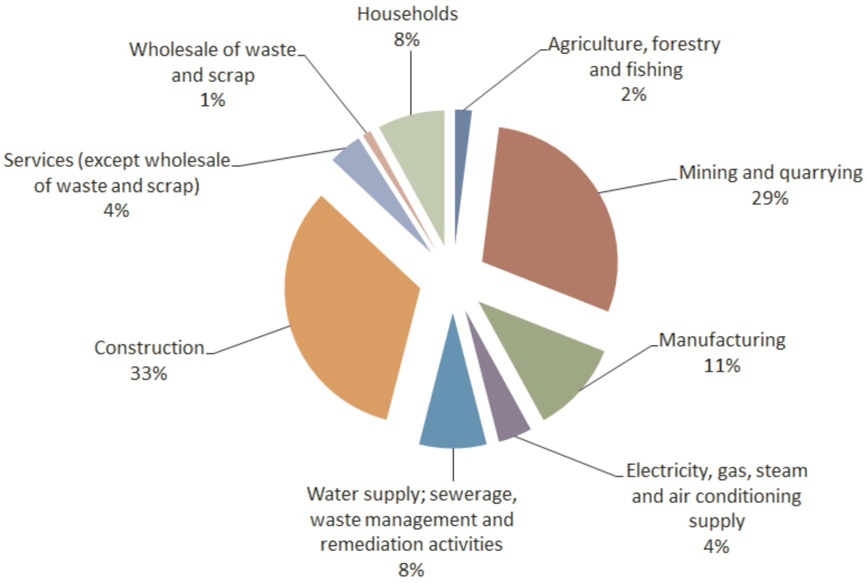


Figure 1-1: Composition of waste generated (wt.%) in EU-28, 2012, according to sector and in terms of mass[2].

Concrete is the main construction material and plays a vital role in the development of current civilisation[1]. According to the statistics from the European Cement Association (CEMBUREAU), 4.3 billion tonnes of cement were produced in 2014 worldwide. It is also estimated that the cement production is about 8% to 12% of concrete production, resulting in about 36 to 53 billion tonnes of worldwide concrete production in 2014[4].The world cement production for 2014 by region and main countries can be seen in Figure 1-2.

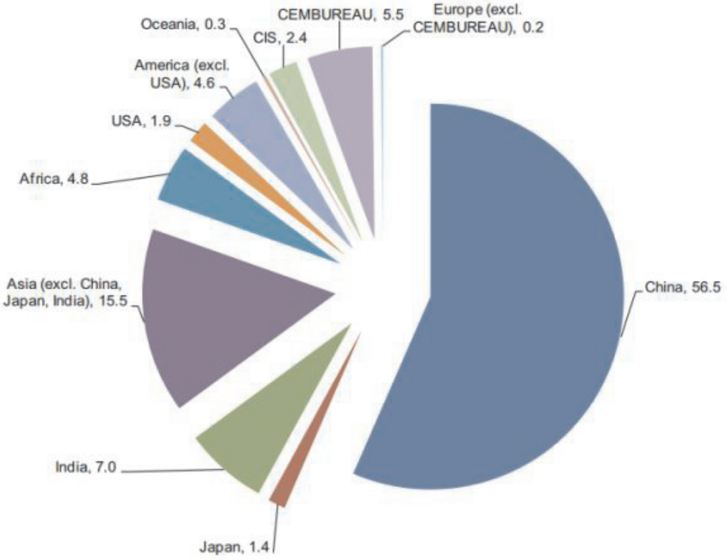


Figure 1-2: Regional breakdown of cement production 2014 in %[4].

In the EU, cement production in the CEMBUREAU member countries is recorded as 235 million tonnes for 2014, which accounts for about 1.9 to 2.9 billion tonnes new concrete production.

On the other hand, about 1,300 million tonnes of waste are generated in Europe each year, of which about 40%, or 540 million tonnes, is CDW[5]. It is estimated that 60-70% of CDW belongs to waste concrete (about 320-380 Mt)[6]. A comparison between the figures related to the production of waste and new concrete, indicates that at present the rate of new concrete production is much higher than that for the waste concrete production. The reason is the large time-lag between the construction and demolition of a building which results in shifting the production of waste concrete to the future.

Following the second World war II, a post-war economic boom (especially in western European countries) happened which resulted in a significant boost in the construction of buildings and infrastructures. Taking the mentioned time-lag into account, the amount of waste concrete is going to rise dramatically in the near future. Based on the revised Waste Framework Directive (WFD), the minimum recycling percentage of 'non-hazardous' CDW, should be at least 70% by weight by 2020. The current average recycling rate of CDW for EU-27 is only 47% and there is still a significant loss of potentially valuable materials all over Europe[7]. This indicates that currently the market for recycled concrete may not be large enough and it needs innovations to create more attractive products.

Presently, the treatment of construction and demolition waste in Europe is mostly based on scenarios 1 and 2 which are indicated in Figure 1-3.

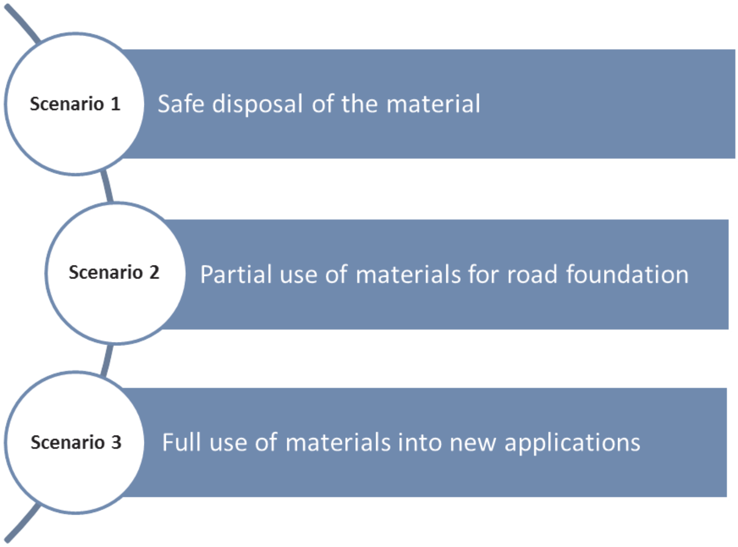
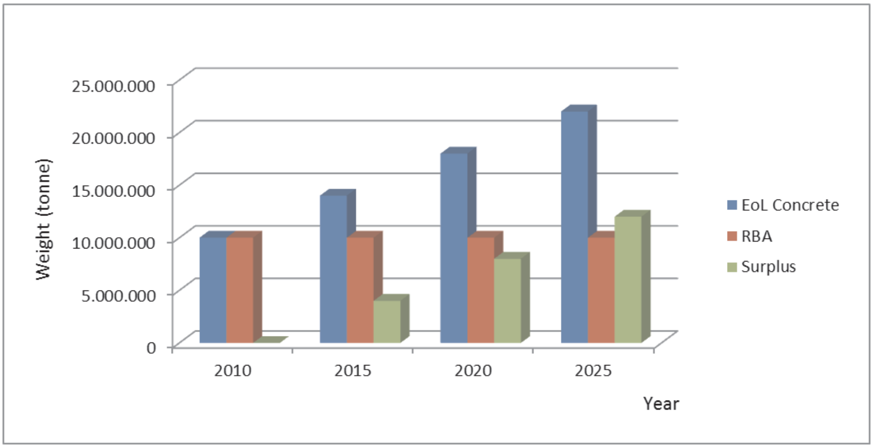


Figure 1-3: Three different scenarios for treatment of construction and demolition waste.

Following Scenario 1, some European countries allow the waste to be land-filled at very low gate fees. However, countries like the Netherlands encourage extensive material re-use through a strategy of selective demolition followed by recycling. With such a strategy, 85% of the material from End Of Life (EOL) building constructions is recovered as relatively pure mono-material fractions, and only 15% ends up as mixed demolition waste that has to be treated in specialized waste treatment facilities. The main mono-material fractions resulting from selective demolition are mineral, steel and wood. They have a neutral to positive value and are ideally suited for re-use at a high level. In particular, the large mineral fraction (85% of all CDW) is crushed off-site or on-site using mobile breakers and is typically applied as a substitute for natural gravel in road foundation (second scenario).

However, despite the fact that road foundation is a useful outlet for recycled aggregates, it is not a sustainable application in the long run. In the coming years, a strong increase of the amount of waste is expected in Europe due to the large number of constructions from the 1950s that are closing to their end of life. At the same time, the demand for road foundation materials is expected to decline with the time due to the reduction in the net growth of infrastructure. Government statistics of the Netherlands, for example, predict that whereas nearly 100% of the EOL concrete is absorbed by the Dutch road sector today, this number will have dropped to below 40% by 2025 (see Figure 1-4).



*RBA: Road Base Aggregates

Figure 1-4: Study of the Dutch government for the end of life concrete demand.

On the other hand, the required technology and business model for fully recycling and re-using of EOL concrete into new concrete is yet beyond what can be achieved by the recycling industry (Scenario 3 in Figure 1-3 is not mature yet).

1.2 CONCRETE COMPARED TO STEEL AND POLYMER

In comparison with some materials such as polymer and steel, there has been less interest for recycling of concrete. Economic motivations and ease of recovery have been key driver for recycling of steel. Environmental impacts supported by public interest and accompanying laws and regulations and governmental subsidies have increased the recovery of polymers. With generally numerous supplies of virgin aggregates and the inert nature of concrete waste (less problems for landfilling), recycling of concrete to concrete has not been a high priority until recently[5]. Table 1-1 compares different economic and environmental indexes which influence the motivations for recycling of the mentioned materials.

Table 1-1: Some economic and environmental indexes which affect drivers for recycling[5, 8-10].

Material	Turnover (b€/y)	Contribution of Recycling to Consumption (wt%)	Primary Materials (€/ton)	Governmental Subsidies (€/ton)	CO_2 Reduction Potential via Recycling (tCO_2/ton)
Polymer	87	2%	1200-1400	3000**	3.73
Concrete	30	8%	35	0-2	0.5*
Steel	90	42%	400	0	0.86

*Amount of CO_2 that can be avoided from decarbonation of limestone in the cement kiln for production of one ton Portland cement clinker

**Figure is related to the packaging plastics in the Netherlands

According to the Interseroh report[8], recycling of one tonne steel and PET polymer results in the reduction of 0.86 and 3.73 tonne in CO_2 emissions respectively.

Based on the CSI report, recycling of concrete into just aggregate, tends not to produce such CO_2 savings[5]. For reduction of CO_2 emissions via concrete recycling, the main source of carbon emissions in concrete should be targeted, which is the cementitious part.

The cement industry is one of the major CO_2 emitting sectors[11]. The use of huge amount of fuel as well as de-carbonation of limestone emits massive amount of CO_2 into atmosphere. It is widely accepted that the production of one tonne of cement emits roughly one tonne of CO_2. Table 1-2 shows the amount of CO_2 that is emitted during the production of cement and concrete.

There is a potential for CO_2 reduction in concrete via concentrating part of the hardened cement paste from end of life concrete into a separate fraction that can be reused as a low-CO_2 feedstock replacing primary limestone.

However, so far this concept is not developed properly and a suitable economic technology to separate hardened cement paste from crushed EOL concrete is not yet available. Thus, up to now, concrete recycling to just aggregates has been considered as CO_2 neutral which reduces environmental and ecologic motivations for concrete to concrete recycling.

Table 1-2: CO_2 emissions from cement and concrete production [12].

Source of CO_2 emission	Amount of CO_2 emitted in production per		% of total CO_2
	Tonne of cement (tonne)	*Cubic meter of concrete (tonne)	
From energy use	0.64	0.236	60
From limestone calcining	0.43	0.158	40
Total CO_2 emission	1.07	0.371	100

*Typical recipe

1.3 CURRENT BARRIERS FOR CONCRETE RECYCLING

Low motivation for recycling of concrete into new concrete has a root in existing cultural, environmental, economic and politic constraints (see Figure 1-5).

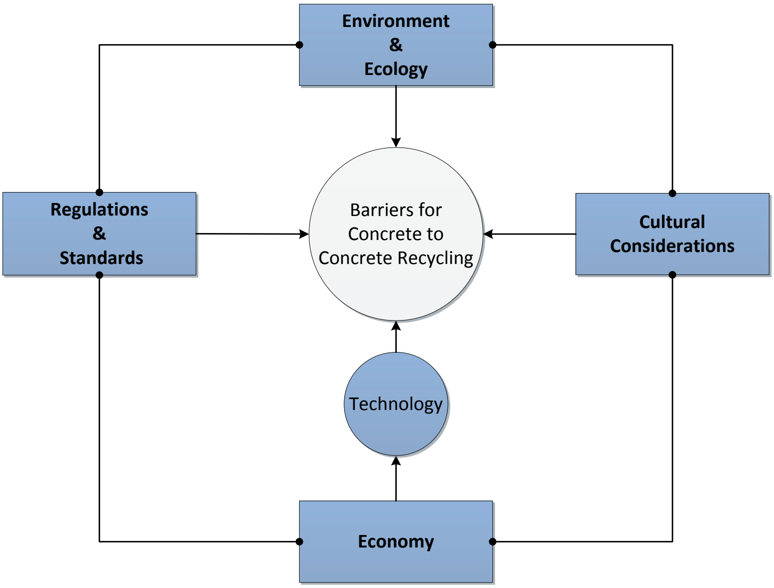


Figure 1-5: Categories of different existing barriers for concrete to concrete recycling.

1.3.1 Regulations, standards and economy

Laws, regulations and standards all impact the approach towards concrete recycling in a given country. Landfill restrictions and taxes, limitations on use of recycled materials in different standards, government green provision strategies, environmental laws and regulations such as restrictions on virgin materials supply, are all determinative [5]. In the UK for example, a levy for natural aggregates and a landfill tax have encouraged the use of recycled aggregate. In addition, the UK government offers grants for recycling infrastructure projects and investigates ways to reduce barriers for full recycling and re-use of end of life concrete. The UK consumed almost 275 Mt of aggregates per annum in 2008 and it was forecast to remain at this level in the next five years. It was also estimated that at the same time around 70 Mt of consumed aggregates were already derived from recycled or secondary sources. The introduction of the UK landfill tax in 1996 resulted in an increase in waste disposal costs for demolition contractors. Subsequently demolition contractors got more motivated to establish new facilities for recycled aggregates production. The impact of this is that the UK currently produces a higher proportion of recycled aggregates than any other European country, with almost all available CDW being diverted from landfill. Table 1-3 shows a comparison of prices charged for recycled and primary aggregates in the UK[13]. On the other hand, in some countries, low economic cost of natural aggregate is a main barrier for using the recycled aggregate.

Table 1-3: Comparison of prices for recycled and primary aggregates in the UK[13].

Product: mm	Recycled aggregate price	Quarried equivalent price
0-4	£5-6	£10-12
0-6	£5-6	£10-12
6-10	£12 (inc delivery)	£15
10-20	£11 (inc delivery)	£15

Another economic factor that will affect the use of recycled aggregate into new concrete is the price of the final product. Market data suggest it needs to be cheaper than concrete made of natural aggregates. This is also necessary in eliminating the conservatism by the marketplace.

To maintain the market confidence and cultural considerations, some important factors such as the consistency of physical properties and the level of contamination in recycled aggregates should be also taken into account. A common misbelief is that recycled concrete aggregate should not be used in structural concrete. Guidelines and regulations often consider the physical limitations of recycled aggregate, but ideally they should also promote its use. Various physical properties of recycled aggregates are affected by the source of the CDW. The risk of contamination in recycled aggregate is one of the biggest barriers to use it. The presence of some road and construction waste materials may contaminate the recycled aggregates. These contaminants include both organic and inorganic materials. Contamination level of uncrushed EOL concrete (before recycling) is easier to assess by visual inspection. However, after crushing of the materials to typical aggregate sizes, the assessment gets more costly. Therefore, business models are more favourable if uncrushed material is transferred to the end user (e.g. mortar/pre-fab concrete facility).

1.3.2 Technology and market barriers

For recycling of concrete, most of the time lack of economic benefits puts constraints on the technology and the business model. The economy of concrete recycling is extremely dependent on the situation and local conditions. Factors such as the quantity of the available natural aggregates, quality and quantity of end of life concrete, public perception for using the recycled products, government policies, standards and regulations, taxes on natural aggregates and landfill are determinative.
In the Netherlands for example, in time, there will be more amount of crushed concrete available in the market. Taking the continual fluctuation in the price of natural aggregate and crushed concrete into account, it is concluded that the maximum cost for the recycling process should not exceed 5 €/ton (see Figure 1-6).

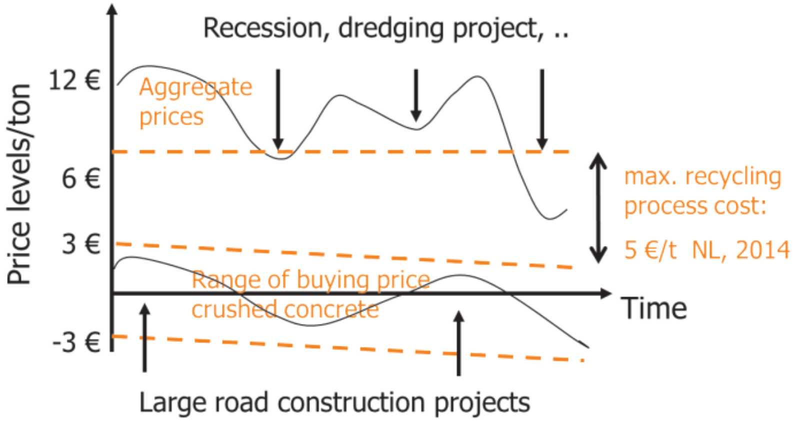


Figure 1-6: Price level of natural aggregate compared to the crushed concrete in time.

Such a low cost of recycling, creates some limitations and constraints for the process technology such as:

- Only cheap unit processes for recycling should be applied on the bulk of the materials (e.g. 0.5-2 €/ton per unit operation).
- Creating any residues after recycling should be avoided or minimised (landfill costs are prohibitive).
- Recycled products should have consistently high quality (comparable or better than natural products) to be able to compete with primary materials in the market.

1.3.3 Environmental and cultural aspects

In addition to all aforementioned barriers, processing technology for concrete recycling should consider possible air pollution and noise impacts as well as energy consumption. To minimize road transport, processing should be done in the urban environment, close to the place in which the secondary aggregates will be used. This requires technologies which produce the minimum amount of noise, dust and pollutions.

On the other hand, according to the Fourth Assessment Report of the IPCC, the building sector has the largest potential for cost-effective mitigation policies. From Figure 1-7 it is clear that some industries including building, have not progressed towards CO_2 reduction even at zero cost. It indicates the existence of technological and cultural barriers in the building industry which make it more conservative with respect to innovation.

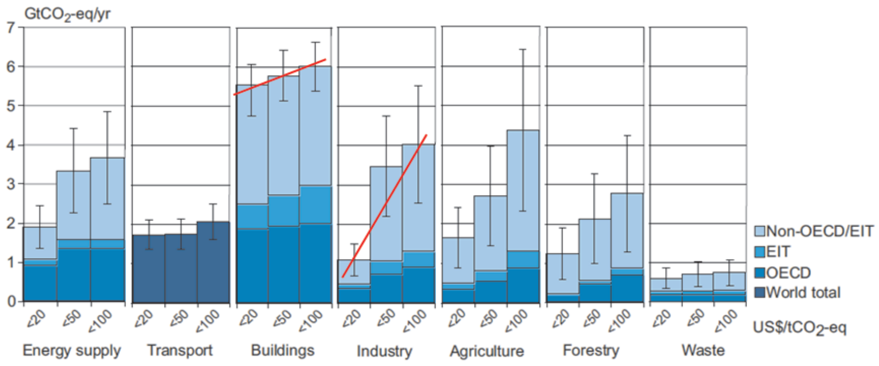


Figure 1-7: Estimated sectoral economic potential for global mitigation for different regions and different cost levels (20$, 50$ and 100$ per ton of avoided CO_2)[14].

As it is mentioned, concrete has a high environmental impact with respect to its input materials, namely in the cement production phase. The Portland cement manufactory process is presently responsible for a significant part of the global emission of

CO_2[11]. A second important environmental impact of the building industry is road transport: in particular traffic congestion and the emissions of dust and CO_2. The transport of concrete from and to building sites amounts to an estimated 75 billion ton-km per year in Europe, or about 100 liters of fuel per m^3 of concrete [15].
Considering the fact that public and private sectors have become aware of the urgency and importance of CDW recycling, the European Commission has taken initiatives towards sustainable treatment and recycling of CDW. In March 2009, the European Commission announced a call for proposals with the subject of "Innovative technologies and eco design recommendations for reuse and recycling of CDW, with a special focus on technologies for onsite solutions". The aim was to develop and promote innovative technologies and system solutions for high-grade construction materials manufactured from high-volume CDW. Onsite processing and/or reuse was a plus for this call. This call resulted in a successful project with the full title of "advanced technologies for the production of cement and clean aggregates from construction and demolition waste" with acronym of C2CA (concrete to cement and aggregates).

1.4 C2CA TECHNOLOGY

In order to achieve a sustainable solution for recycling of concrete into new concrete the following goals should be reached:

1. To widely replace primary raw building materials through recycling of end of life concrete.
2. To achieve a substantial reduction in road transport of building materials.
3. To create a serious cut in CO_2 emission from cement production.

A wide, efficient and quick replacement of primary raw building materials by recycled materials besides a significant reduction in road transport and creating a considerable cut in CO_2 emission requires innovation of business model and technology.
The C2CA concrete recycling technology aims at a cost effective system approach to recycle end of life concrete to hardened cement and clean aggregates. It applies a number of innovative technologies to make the product of the concrete recycling plant suitable as input materials for cement and mortar or pre-cast concrete industry (see Figure 1-8). The technologies considered are smart demolition to produce crushed concrete with low levels of contaminants, followed by mechanical upgrading of the material on-site into an aggregate product with sensor-based on-line quality assurance and a cement-paste concentrate that can be processed (off-site) into a low-

CO_2 input material for new cement. After crushing and sorting out big contaminants, liberation of the cement paste is promoted by several minutes of grinding in an autogenous mill while producing as little as possible new fine silica. A new low-cost classification technology, called Advanced Dry Recovery (ADR) is then applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles. ADR uses kinetic energy to break the bonds that are formed by moisture and fine particles and is able to classify materials almost independent of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. The finer fraction of crushed EOL concrete is problematic due to the moist mixture of silica aggregates, cement paste and water (10-15%), contaminated with 0.5-1% of foreign materials such as wood, metal and plastics.

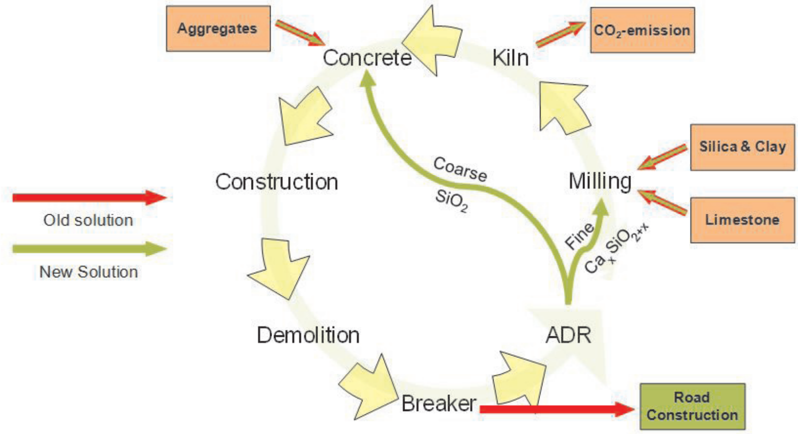


Figure 1-8: Old route and proposed novel closed cycle for recycling of concrete to cement and aggregate (C2CA).

The idea of using ADR for concrete recycling comes from its successful application in bottom-ash recycling. Similar to the crushed concrete, bottom-ash has difficulties for separation of the -1mm fines due to the moisture and this problem was solved using ADR. Since the ADR technology can deal with moist materials, it can produce gravel and sand from end of life concrete on-site, and with proper logistics, significant savings in road transport of building materials can therefore be achieved. Figure 1-9 shows the mobile version of ADR that is used for bottom-ash recycling allowing the equipment to be transported rather than the material.

Figure 1-9: Mobile and transportable version of ADR.

1.4.1 Contribution of C2CA in CO_2 reduction

In the Netherlands, about 14 Mt of end of life concrete is produced per year. It is estimated that at least 50wt% of this amount is suitable to process by ADR. ADR fine fraction is a rich source of hardened cement that can be used as low-CO_2 feedstock for the production of new clinker in the cement kiln. Based on a CE Delft report, the potential for CO_2 reduction using ADR fines in cement production (just in the Netherlands) is conservatively estimated as 60000 tonne CO_2/year [16]. It is a very important achievement which can increase the social attention towards concrete recycling and its ecological and environmental advantages.

1.4.2 C2CA solution for economic and technological barriers

To overcome the existing technological barriers for concrete to concrete recycling, first of all, C2CA applies a combination of economic and innovative technologies while the cost of each unit process does not exceed 2 €/ton. Secondly, after the recycling process, very small amount of residues (contaminants such as wood, plastic and metal) will be left. This full recovery of materials leaves almost no cost for landfilling. Thirdly, the on-line quality control sensors applied in C2CA process will assure the quality of the streams that are naturally prone to substantial variations in composition. Thus, the main challenge of the mortar or cement producers that is about inconsistency in their products qualities using recycled materials, will be solved.

1.4.3 C2CA business model in brief

In order to make the concrete to concrete recycling business more attractive and profitable, the C2CA route applies a new business model which is based on minimising trading fees and reducing the risk of quality issues and lack of transparency in quality. To minimise the trading fees, C2CA route confines the ownerships of the EOL concrete to a limited number of actors. In a conventional business model of concrete recycling, the ownership of EOL concrete is transferred among different actors step by step from the production to recycling and re-use of EOL concrete (see Figure 1-10). Such activity results in an extra increment in the overall price of aggregates/recycled products and creates more economic barriers. However, based on the C2CA route, only the construction company and the client will have the shared ownership of the EOL concrete from the beginning to the end. Such a combination of activities with limited number of actors has important advantages in creating a circular economy for the building sector. For one, the construction company is in control of the quality of the recycled materials used in the new buildings and the costs associated with quality risks are strongly reduced. Another strong point is that the construction company is both the supplier and the user of building materials for the mortar or pre-fab facilities, and so will tend to use its favourable negotiation position to enforce a maximum and optimal re-use of its own material.

Figure 1-10 : Different steps of transferring the ownership of EOL concrete in the conventional concrete recycling business.

To create even more transparency in quality, the C2CA concrete recycling process is preferably performed at the mortar or pre-fab concrete facilities. In this case, recycling of EOL concrete and re-use of the recycled aggregates takes place in the same location and creates a favourable economy of scale. This activity is, in fact, a joint venture between mortar or pre-fab concrete production and parties who are constructing and demolishing on the site. Therefore, there will be no trading of the materials. By creating this joint venture besides applying the online quality control systems, more trust and transparency will be among parties involved in this business. Figure 1-11 shows approximate costs of each unit process in the C2CA process and the selling price of recycled products.

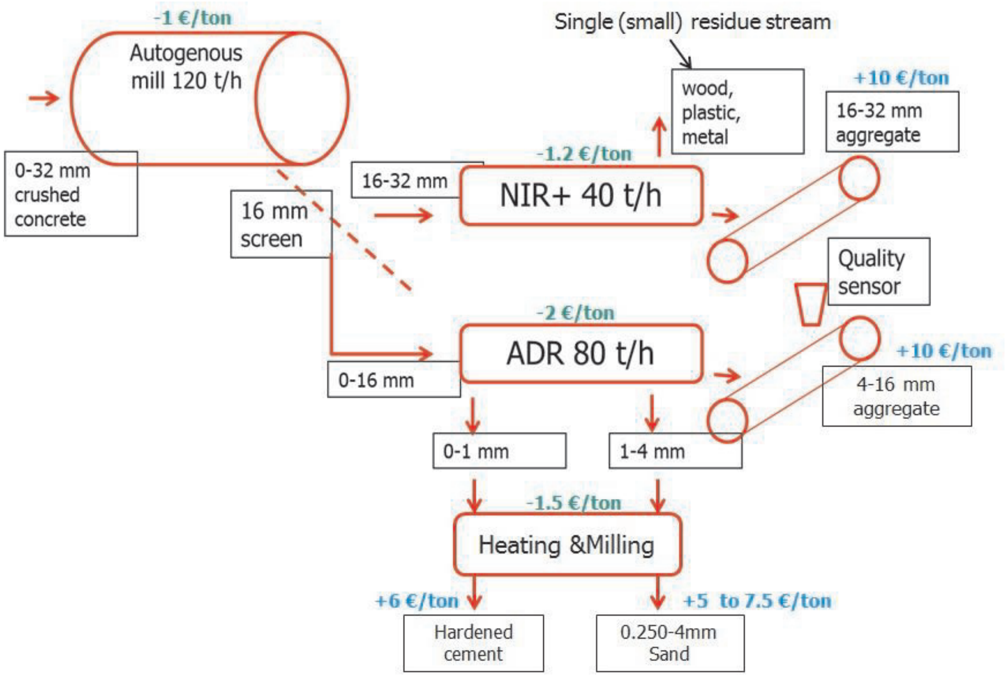


Figure 1-11: Simplified process flow sheet of the C2CA process. Approximate costs of each unit process and the selling price of recycled products are shown in green and blue colours respectively. The maximum particle size of the crushed concrete as the process input material might change based on the market demand and currently it is changed from 32 mm to 22 mm.

1.5 SCOPE OF THE THESIS

This thesis investigates the principle and key processes of the C2CA concrete recycling route aiming to develop a technology within the existing environmental, economic, cultural and politic constraints. To make full use of the benefits of the C2CA route, advanced ADR technology and autogenous milling should be optimized to create a highly concentrated hardened cement and clean aggregate.

A solution for recycling of ADR fines to valuable and applicable streams (hardened cement and clean sand) should be found. The number of contaminants in all produced recycled fraction should be minimized to its lowest level. Therefore, alternative ways such as sensor sorting should be studied to remove contaminants. The effects of different process variables during concrete recycling or new concrete production on the quality of the final products should be investigated.

All investigations about the aforementioned issues are converted to different scientific articles and chapters of this thesis are organized based on those articles. Minor overlapping of the information is, therefore, inevitable. This thesis includes in total eight chapters covering research over the C2CA concrete recycling process(see Figure 1-12).

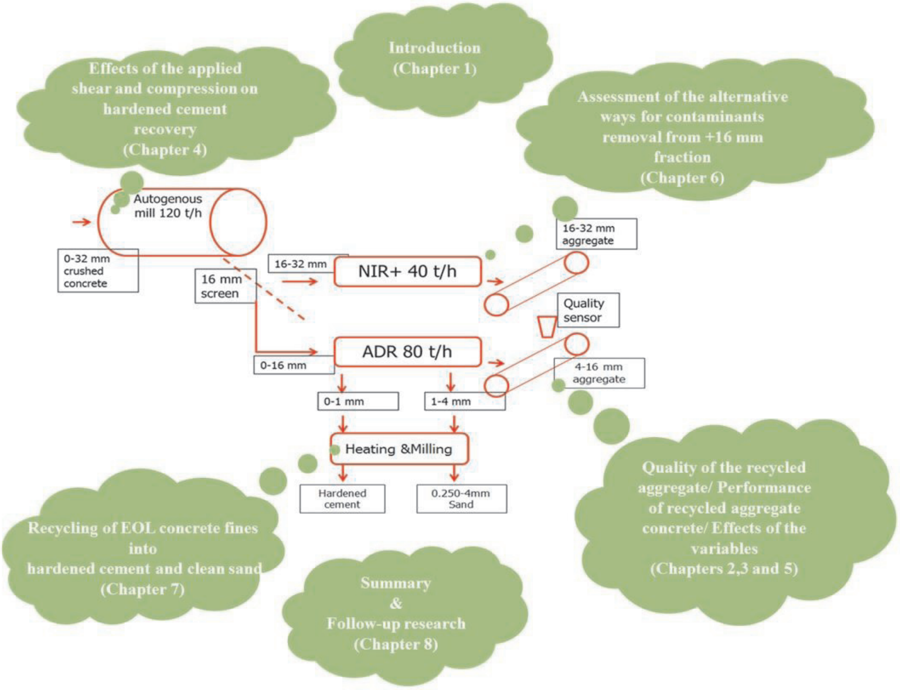


Figure 1-12: Schematic outline of the thesis.

In the following, the titles of the articles including their abstracts are listed:

- **Mechanical Recycling of EOL Concrete into High-Grade Aggregates**

Recycling End of Life (EOL) concrete into high-grade aggregate for new concrete is a challenging prospect for the building sector because of the competing constraints of low recycling process cost and high aggregate product quality. A further complicating factor is that, from the perspective of the environment, there is a strong societal drive to reduce bulk transport of building materials in urban environments, and to apply more in situ recycling technologies for CDW. The European C2CA project investigates a combination of smart demolition, grinding of the crushed concrete in an autogenous mill to increase the liberation of cement mortar from the surface of aggregates and a novel dry classification technology called ADR to remove the fines. The feasibility of this recycling process was examined in a demonstration project involving 20,000 tons of EOL concrete from two office towers in Groningen, the Netherlands. Results show that the +4 mm recycled aggregate compares favourably with natural aggregate in terms of workability and the compressive strength of the new concrete, showing 30% higher strength after 7 days.

- **Performance of recycled aggregate concrete based on a new concrete recycling technology**

This paper concentrates on the second demonstration project of C2CA, where EOL concrete was recycled on an industrial site. After recycling, the properties of the produced Recycled Aggregate (RA) were investigated, and results are presented. An experimental study was carried out on mechanical and durability properties of produced Recycled Aggregate Concrete (RAC) compared to those of the Natural Aggregate Concrete (NAC). The aim was to understand the importance of RA substitution, w/c ratio and type of cement to the properties of RAC. In this regard, two series of reference concrete with strength classes of C25/30 and C45/55 were produced using natural coarse aggregates (rounded and crushed) and natural sand. The RAC series were created by replacing parts of the natural aggregate, resulting in series of concrete with 0%, 20%, 50% and 100% of RA. Results show that the concrete mix design and type of cement have a decisive effect on the properties of RAC. On the other hand, the substitution of RA even at a high percentage replacement level has minor and manageable impact on the performance of RAC. This result is a good indication towards the feasibility of using RA in structural concrete by modifying the mix design and using a proper type of cement.

- **An experimental study on the recovery of the hardened cement from crushed end of life concrete**

In the C2CA concrete recycling process, autogenous milling of the crushed End of Life (EOL) concrete is a mechanical method to remove cement paste from the surface of aggregates. During autogenous milling, the combination of shearing and compression forces promotes selective attrition and delivers a better liberation. In order to investigate the effects of shear and compression on the cement recovery and specify the importance of them, a new set-up is designed and constructed. This set-up permits aforesaid forces to be determined and controlled. For experimental design, the MINITAB 16 software was used and 13 different experimental runs based on varying shear and compression forces were conducted. After each experiment, the amount of cement recovery using XRF analysis, water absorption of the recycled aggregates and energy consumption during the process were measured. Results show that both shear and compression forces have influence on improving the cement recovery. With simple changes in the setting of an autogenous mill like bed height or residence time the need for high-cost secondary crushing during concrete recycling could be eliminated.

- **The relation between input variables and output quality in the C2CA process**

The C2CA process consists of a combination of smart demolition, gentle grinding of the crushed concrete in an autogenous mill, and a novel dry classification technology called ADR to remove the fines. The main factors in the C2CA process which may influence the properties of Recycled Aggregates (RA) or Recycled Aggregate Concrete (RAC) include the type of Parent Concrete (PC), the intensity of autogenous milling (changing the amount of shear and compression inside of a mill) and the ADR cut-size point (usage of +2mm or +4mm RA in the new concrete). This study aims to investigate the influence of implied factors on the quality of the RA and RAC. To conduct the study, first of all, three types of concrete which are mostly demanded in the Dutch market were cast as PC and their fresh and hardened properties were tested. After near one year curing, PC samples were recycled independently varying the type of PC and intensity of the autogenous milling . Experimental variables resulted in the production of eight types of RA. The physical, mechanical and durability properties of the produced RA were tested and the effect of the experimental variables on their properties were investigated. According to the results, the type of PC is a prevailing parameter for the final properties of RA, in comparison with the milling intensity. Moreover, it is observed that a variation in the milling intensity mostly influences the properties of RA produced from a lower strength PC. Experiments were followed by studying the performance of the RA in the new concrete. Four types of RAC were produced based on the modified recipe of their corresponding PCs. For the modification of the recipes, water absorption and density of RA were taken into account while the amount of applied cement and consistency class was kept similar to the corresponding PC. Experimental results show that the compressive strengths of all produced RAC samples were higher than PC, especially at early ages. The increasing rate of compressive strength for different types of RAC was found to be mostly influenced by the type of PC and the autogenous milling intensity. Among various autogenous milling intensities, milling at medium shear and compression delivers better properties for RA and RAC. Good performance of RAC with the incorporation of 2-4mm ADR fines and RA, confirms the possibility of setting ADR cut-size point on 2 mm.

- **Assessment of the contaminants level in Recycled aggregates and alternative new technologies for contaminants recognition and removal**

One of the main challenging problems associated with the use of Recycled Aggregates (RA) is the level of mixed contaminants. For utilizing RA in high-grade applications, it is essential to monitor and minimise the content of the pollutants. To this extent the C2CA concrete recycling process investigates a combination of smart demolition, followed by new innovative technologies to produce high-grade secondary aggregates with low amount of contaminants. This paper firstly reports the level of contaminants in different fractions of recycled aggregates coming from a real case study. Results show that the wood content of 4-16 mm recycled aggregates is well within the strictest limit of the EU standard. However, there are still large visible pieces of wood and plastic in the +16 mm RA fraction which, albeit within the standards, does not satisfy the users. In order to solve this problem the feasibility of applying two existing technologies (near infrared sensor sorting and wind sifting) to remove contaminants, is studied. Furthermore, two types of online quality control sensors (hyper spectral imaging and laser induced breakdown spectroscopy) are introduced and a summary of their recent developments towards the quality control of RA are presented (Information about the HSI and LIBS technologies are available in the paper but not in this thesis).

- **Recycling of EOL concrete fines into hardened cement and clean sand**

One of the massive by-products of concrete to concrete recycling is the crushed concrete fines fraction, that is often 0-4mm. Using this fraction into new concrete is famous to be detrimental, due to its high water absorption and mixed contaminants. Considering the shortage of natural resources and the goal of achieving sustainable developments, many studies have been performed on re-use of recycled concrete coarse and fines in new building materials. Although the construction sector is to some extent familiar with the utilization of the coarse fraction of crushed concrete, at present there is no high-quality application for crushed concrete fines. Here we present an effective recycling process on lab scale to separate the cementitious powder from the sandy part in the crushed concrete fines and deliver attractive products with the minimum amount of contaminants. This separation could facilitate the high-quality reuse of the hardened cement rich fraction in virgin cement production. This study aims to achieve preliminary information for designing an industrial scale recycling set-up for fines. Results show that by heating the materials to 500°C for 30 seconds, the time of milling is diminished by a factor of three while the quality of the products satisfies well the market demand.

1.6 ACKNOWLEDGEMENTS

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CHAPTER 2

Mechanical Recycling of EOL Concrete into High-Grade Aggregates

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This chapter is based on the published article:
Lotfi S, Deja J, Rem P, Mróz R, van Roekel E, van der Stelt H. Mechanical recycling of EOL concrete into high-grade aggregates. Resources, Conservation and Recycling. 2014;87:117-25.

2.1 ABSTRACT

Recycling End of Life (EOL) concrete into high-grade aggregate for new concrete is a challenging prospect for the building sector because of the competing constraints of low recycling process cost and high aggregate product quality. A further complicating factor is that, from the perspective of the environment, there is a strong societal drive to reduce bulk transport of building materials in urban environments, and to apply more in situ recycling technologies for CDW. The European C2CA project investigates a combination of smart demolition, grinding of the crushed concrete in an autogenous mill to increase the liberation of cement mortar from the surface of aggregates and a novel dry classification technology called ADR to remove the fines. The feasibility of this recycling process was examined in a demonstration project involving 20,000 tons of EOL concrete from two office towers in Groningen, the Netherlands. Results show that the recycled aggregate compares favourably with natural aggregate in terms of workability and the compressive strength of the new concrete, showing 30% higher strength after 7 days.

2.2 INTRODUCTION

Sustainable solutions for Construction and Demolition Wastes (CDW), entailing their efficient and environmentally friendly recycling into high-grade secondary building materials, are of increasing interest from the point of view of the European Commission, yet they are beyond what can presently be achieved by the recycling industry[1]. In the coming years, a strong increase of the amount of waste is expected in Europe because and the same time, the demand for road foundation materials, an important outlet for the stony fraction of CDW, is expected to decline with time, due to the reduction in the net growth of infrastructure. By recycling part of the concrete fraction of CDW into high quality construction materials like aggregate and cement for new concrete, it is possible to take advantage of the surplus of waste. However, so far as there are many unsolved problems associated with the quality of recycled aggregate, this application is limited.

In order to provide a sustainable solution, Recycled Aggregate Concrete (RAC) must be suitable for a broad range of applications, be affordable and be able to compete with primary materials in terms of workability, compressive strength and durability. To satisfy all these requirements, it is crucial to at least reduce the contents of (floating) contaminants and fines of the aggregate. The simplest option to realize this is to dilute recycled aggregate (RA) with natural aggregate (NA) down to levels of 20% replacement of total aggregate by RA[2]. When RA replacement is less than 20% the influence is negligible[3], but of course dilution is not a sustainable practice eventually. It is proposed to remove strongly moisture absorbing particle size fractions (fines) from the RA in order to improve compressive strength[4]. Removing fines also reduces problems of caking during storage and high level of moisture absorption. However, so far, this procedure has been practical only for fully dry crushed concrete by screening or by wet classification methods. Drying the materials to lower the moisture content prior to screening is unattractive because it consumes a lot of energy while wet methods produce sludge which has to be treated or land-filled, often at considerable costs[5]. Another problem is that both drying and wet technologies are less suitable for in situ recycling in an urban environment.

Other ways to increase the quality of aggregates are acid processing, thermal-mechanical processing and purely mechanical treatment. The objective of these methods is to reduce the adhered mortar from the surface of aggregates, since surface mortar affects the absorption and density of aggregate and ultimately the performance of the concrete[6]. Tam et al. studied the effects of a pre-soaking treatment on reducing the amount of mortar attached to the surface of recycled aggregates[7]. Iizuka et al. proposed a mixed chemical and mechanical process to extract fine aggregates with the size of 0.6-5 mm from waste concrete[8]. Shima et al. developed technologies to produce high quality aggregate from crushed concrete by a combination of heating and rubbing or grinding[9]. In addition to the above, some purely mechanical liberation techniques have been proposed in Japan; eccentric-shaft rotor and mechanical grinding. In the mechanical grinding method, a drum is divided into small sections with partitions. The mortar is removed from the aggregate by interaction with steel balls placed in each of the rotating partitioned sections of the drum[10].

In spite of the research carried out on different aspects of concrete recycling and making RAC, there is no accepted comprehensive approach today that delivers an aggregate of consistently high quality at economically and environmentally attractive conditions.

2.3 THE C2CA PROJECT

The C2CA project aims at a cost-effective system approach for recycling high-volume EOL concrete streams into prime-grade aggregates and cement (see Figure 2-1). The technologies considered are smart demolition to produce crushed concrete with low levels of contaminants, followed by mechanical upgrading of the material on-site into an aggregate product with sensor-based on-line quality assurance and a cement-paste concentrate that can be processed (off-site) into a low- CO_2 input material for new cement. To achieve in situ recycling of the aggregate is one of the main goals of the C2CA project. Therefore, liberation of the cement paste, as well as the sorting and size classification of the aggregate, is performed purely mechanically and in the moist state, i.e. without prior drying or wet screening. This choice reduces process complexity and avoids problems with dust or sludge. After crushing and sorting out big contaminants, liberation of the cement paste is promoted by several minutes of grinding in a small-diameter (D = 2.2m) autogenous mill while producing as little as possible new fine silica. A new low-cost classification technology, called Advanced Dry Recovery (ADR) is then applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles[5,11]. ADR uses kinetic energy to break the bonds that are formed by moisture and fine particles and is able to classify materials almost independent of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product and a fine fraction including the cement paste and contaminants such as wood, plastics and foams (see Figure 2-2).

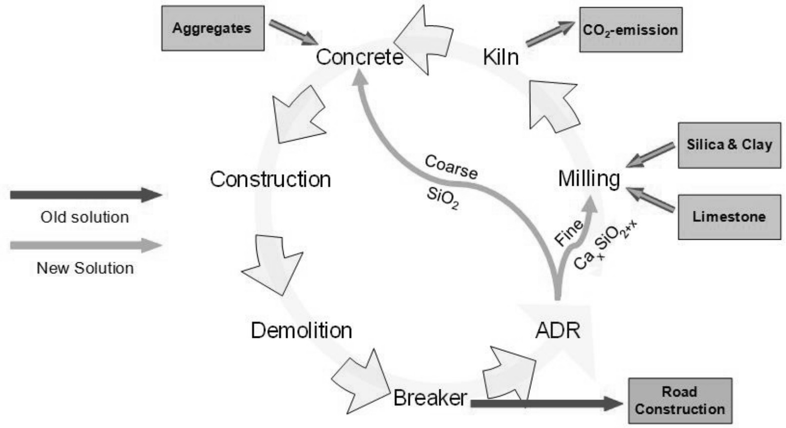

Figure 2-1: Existing vs. proposed novel closed cycle for concrete recycling.

In order to reduce cost and make it possible to ship the produced recycled aggregate to a mortar facility immediately, The C2CA project develops two types of sensors for automatic on-line quality control and quality assurance. The concept is to avoid the need for laboratory analysis and intermediate storage, minimize transport of bulk materials and combine, if possible, quality and end-of-waste certification at the site, without human intervention. A schematic representation of the C2CA process is shown in Figure 2-3.

Figure 2-2: Products from crushed concrete by ADR: Coarse (left) and Fine (right)[5].

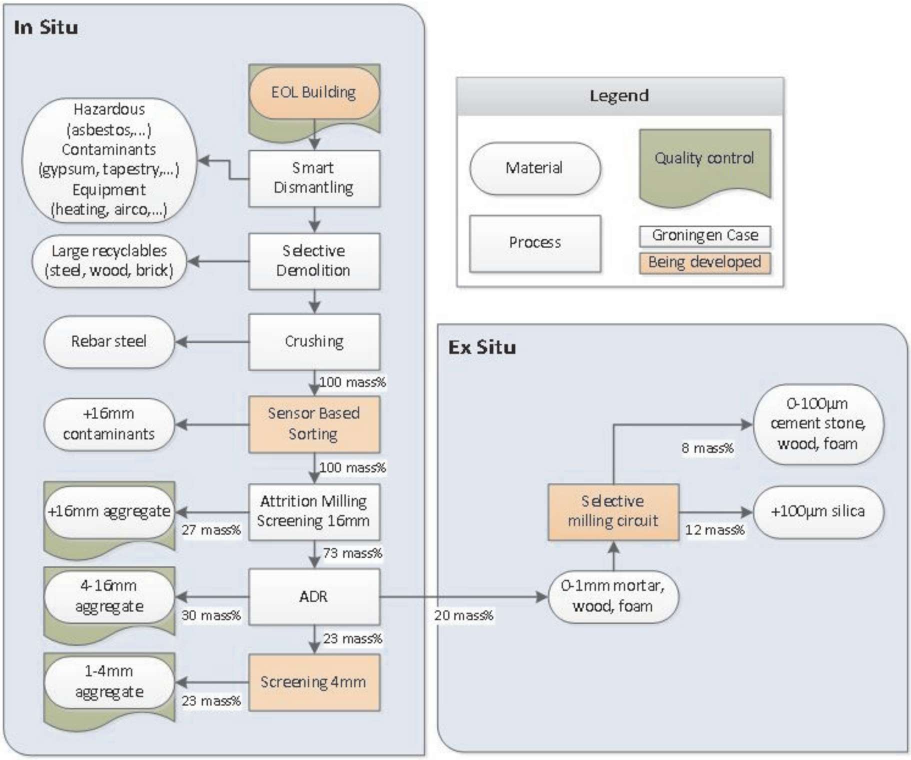

Figure 2-3: General layout of the C2CA technology showing the mass flow distribution for the concrete fraction. Some steps of the mechanical process and quality assessment that were not yet implemented in the first demonstration case are shown in dark colour.

A second major goal of the project, next to in situ processing and local reuse of the aggregate, is to help decrease CO_2-emissions in cement production by concentrating part of the cement paste from EOL concrete into a separate fraction that can be re-used as a low-CO_2 feedstock replacing primary limestone. Already in 2000, world cement production amounted to 8.6% of global CO_2-emissions from fossil fuels[12]. Perhaps the most challenging goal of the C2CA project is to understand how Europe may encourage the in-situ recycling of EOL buildings into high-grade new building materials. For this, the C2CA project focuses on projects in which construction companies take the lead both in demolishing and recycling EOL buildings as well as in constructing new buildings. Such a combination of activities in a single actor has important advantages in creating a circular economy for the building sector. For one, the construction company is in control of the quality of the recycled materials used in the new buildings and the costs associated with uncertainty about this quality are strongly reduced. Another strong point is that the construction company is both the supplier and the user of building materials, and so will tend to use its favourable negotiation position to enforce a maximum and optimal re-use of its own material.

2.4 MATERIALS AND METHOD

2.4.1 EOL concrete

The first case study of the C2CA project involved the demolition of a governmental complex in the province of Groningen in the Netherlands and the building of an underground garage from concrete with recycled aggregate. The scope of the demolition part of the project consisted of two identical high-rise towers (KB2 and KB6) and several low-rise buildings marked with the blue dotted line in Figure 2-4. In the 70's and 80's the Dutch construction sector used asbestos in the buildings. Therefore, prior to the dismantling asbestos was removed. The further strategy for the dismantling of the EOL-buildings in Groningen involved the detailed removing of all materials from the concrete skeleton before starting off the demolition: air-conditioners, radiators, lamps, piping systems of water and heating, electric cables, carpets, gypsum plates from ceilings and walls, window glass, frames of doors and windows etc. (see Figure 2-5).

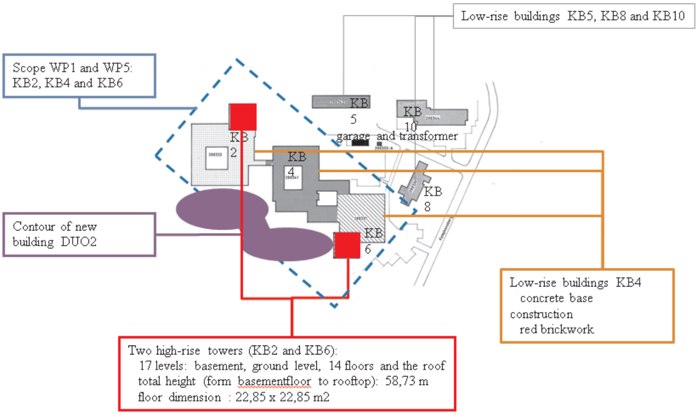

Figure 2-4: Overview of the end of life buildings.

Figure 2-5: Materials resulting from the dismantling of the EOL-buildings in Groningen.

For the demolition of the two towers (KB2 and KB6), three different methods were investigated from which two methods were applied: the top-down method to demolish the top 12 floors, and short-reach method to demolish the lowest 2 floors of the towers. Different types of concrete were used for structural floors, structural beams, pillars and facades in the two towers (see Table 2-1). The quality class of the parent concrete mixture was K-300 (325kg cement per m^3). According to the visual evidence two types of cement, Portland and CEM III/B (historic name: blast furnace-A), exist in this EOL concrete. Clean EOL concrete from the two towers was collected in two batches of 10000 ton each. Both batches were crushed applying an industrial jaw crusher (Kleemann: SSTR1400) to particle sizes smaller than 40 mm. Jaw crushers are reported to perform better than impact crushers in the case of aggregates recovery (Hansen, 1990), because they will crush only a small proportion of the original aggregate particles in the old concrete if they are set at 1.2 -1.5 times the maximum size of original aggregate. Figure 2-6 shows the particle size distribution of the crushed concrete according to norm EN 933-11:2009 for the first batch. A sample of circa 40 tons of this material was processed while varying conditions of the milling process and samples were taken of the +4 mm ADR aggregate product for testing.

Table 2-1: Overview of the amounts of clean EOL concrete recovered from each tower.

Storey	Structural floor (m^3)	Structural beam (m^3)	Pillar	Facade	Storey total
-1	915	0	44	0	959
0	104	51	93	0	248
1	104	51	44	24	222
2	104	51	44	24	222
3	104	51	44	24	222
4	104	51	44	24	222
5	104	51	44	24	222
6	104	51	44	24	222
7	104	51	44	24	222
8	104	51	44	24	222
9	104	51	44	24	222
10	104	51	44	24	222
11	104	51	44	24	222
12	104	51	44	24	222
13	104	51	50	24	228
14	104	51	52	24	230
roof	126	51	0	20	197
Total	2599	813	770	351	4532

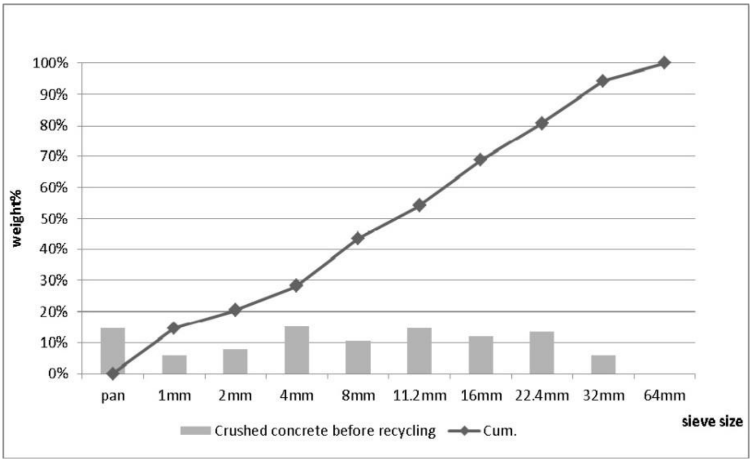

Figure 2-6: Particle size distribution of the crushed concrete.

A floating test of the crushed EOL concrete of the first batch according to EN 12620 (for application of the material as coarse recycled aggregate) shows that the total amount of floating contaminations is less than 1 cm^3/kg. This level of floats satisfies the FL2- specification of EN 12620. It confirms that the EOL concrete comes from a careful demolition procedure, that minimises the amount of coarse contaminants. The distribution of floating materials in the +4 mm fractions is shown in Table 2-2.

Table 2-2: Floating materials in crushed concrete.

Size of crushed aggregates(mm)	floating materials [cm^3/ per kg of crushed concrete]
4-8	0.38
8-11.2	0.09
11.2-16	0.05
16-22.4	0.08
22.4-31.5	0.14
Total	**0.74**

2.4.2 Recycling process

Crushed concrete was used to carry out experiments with a simplified version of the C2CA process. A mill (5.6 meter length, 2.2 meter diameter and 12RPM speed) with maximum internal capacity of 16 tons was installed. Milling of materials was followed by a rotating 16 mm screen and an ADR with a capacity of 60 tons per hour. Figure 2-7 shows the flowchart of the process. Experiments were conducted applying two different amounts of loading inside of the mill. In both experiments, the residence time of the materials inside of the mill was 12 minutes and around 30 (wt%) of mill input was refluxing coarse fraction with the size of +16mm.

Table 2-3 lists the amounts of loaded crushed concrete inside of the mill as well as the coding of the experiments and products.

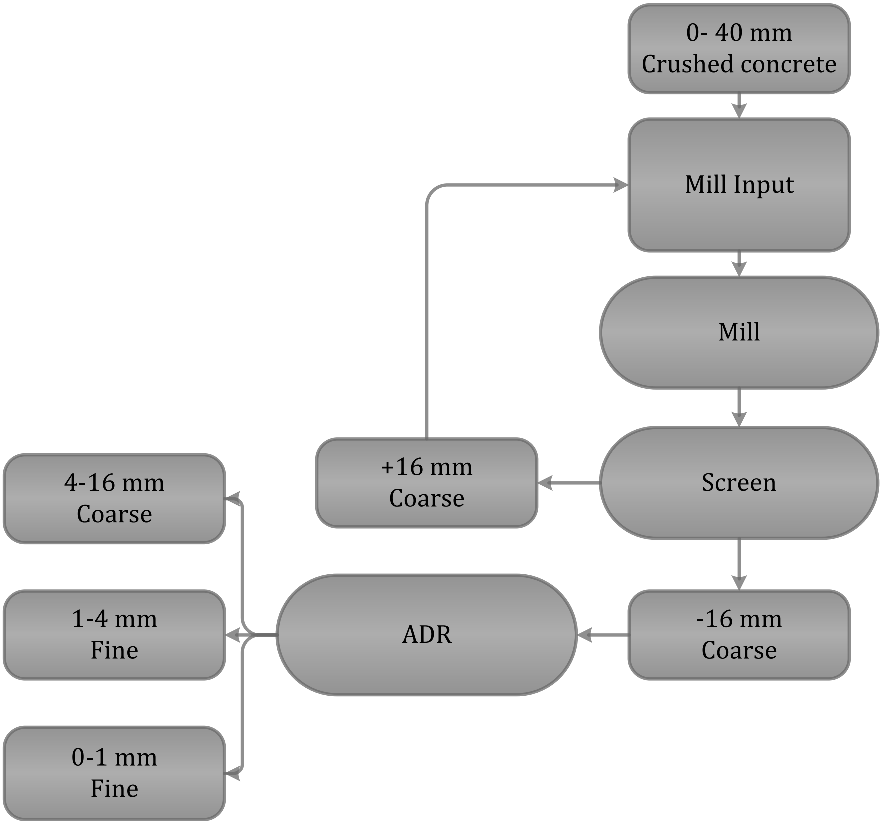

Figure 2-7: Flowchart of the recycling process.

Table 2-3: Recycling experiments coding and amount of loading inside of the mill.

experiment code	total mill input (ton)	Reflux of +16 mm into the mill	ADR products codes		
			coarse (4-16 mm)	fine (1-4 mm)	fine (0-1mm)
3-BS	8.7	yes	3-BS2	3-BS3	3-BS4
4-BS	15.1	yes	4-BS2	4-BS3	4-BS4

2.5 RESULTS AND DISCUSSION

2.5.1 Performance of ADR

The performance of ADR was evaluated by choosing samples from experiment 4-BS. The moisture content and particle size distribution of ADR input and outputs was determined (Table 2-4).

Table 2-4: Moisture content of ADR input and outputs.

Moisture content of samples	unit	ADR input-4BS	4-BS2	4-BS3	4-BS4
	gr/gr	5.79%	4.73%	7.51%	13.10%

It is clear that the moisture is mostly associated with the fine fraction and by removing this fraction, the originally sticky material becomes loose and processable [11]. The 1-2 mm products of the ADR are the results of an air-knife and so this product has the highest wood content compared with other products. Particle size distributions of ADR input and outputs are shown in Figure 2-8 The recovery of each size fraction into all three products and the cut-points is shown in Figure 2-9.

2.5.2 Properties of RA and performance of RAC

Laboratory tests were conducted on the coarse ADR product samples 3-BS2 and 4-BS2 to evaluate the properties of recycled aggregates (RA). Table 2-5 shows the used standards and Table 2-6 shows the results of the tests. ADR coarse product (3-BS2) was selected for testing into new concrete. The water absorption capacity of RA (3-BS2) is 5.4 (wt.%) which is typical for CDW coarse aggregates with density 2000-

2400 kg/m^3 originating from demolition of concrete constructions. The guideline prepared by RILEM recommended recycled coarse aggregates for concrete production if their water absorption is between 3-10% [13].

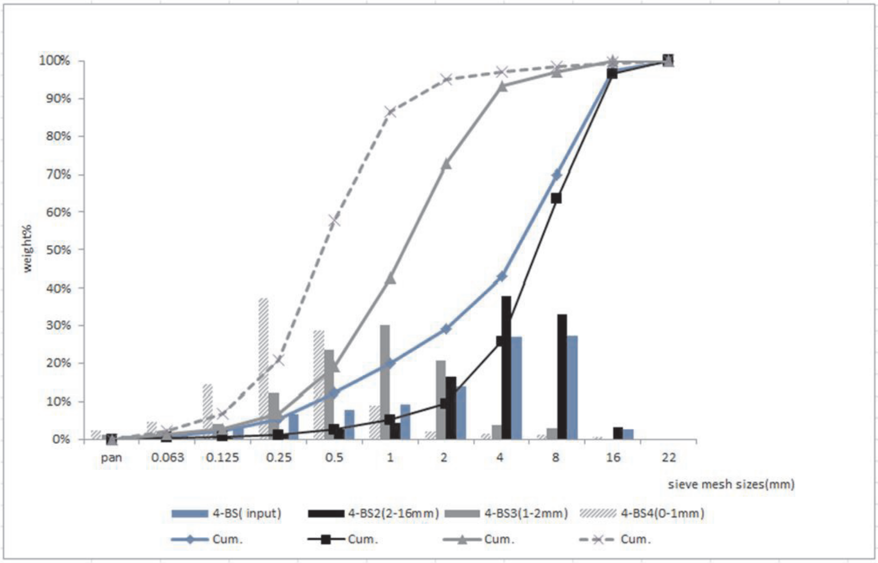

Figure 2-8: Particle size distribution of ADR input and outputs.

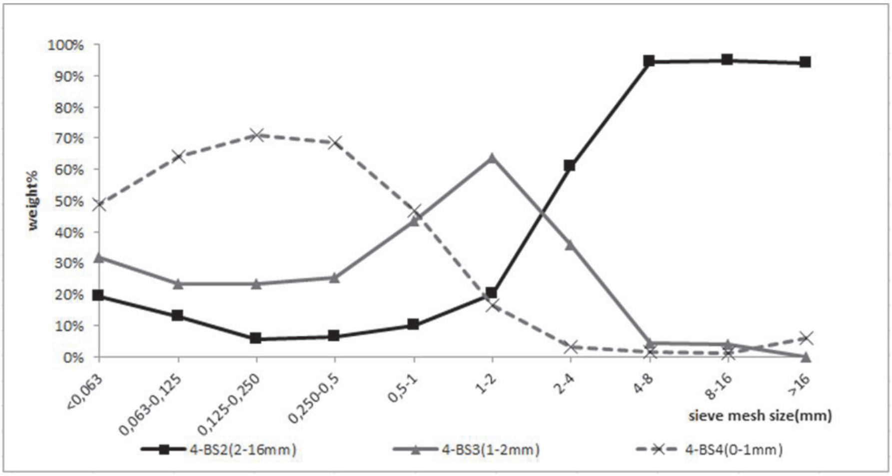

Figure 2-9: The recovery percentage of each size fraction into the three products of ADR.

Table 2-5: Standards used for determining properties of recycled aggregate.

Test	Standards
particle shape (flakiness index)	EN 933-3
particle shape(shape index)	EN 933-4
Resistance to fragmentation (LA coefficient)	EN 1097-2
resistance to crushing according to Polish National Standard	PN-B-06714-40

Table 2-6: Properties of recycled aggregates (4-16 mm ADR products).

Sample	Flakiness index	shape index	LA coefficient	Crushing resistance(Xra)
3-BS2	6.45	8	62.9	15.5
4-BS2	5.53	8	62.8	15.4

Recycled aggregate tends to absorb more water in comparison with natural aggregates due to the residue of the mortar adhering to the original aggregate [14]. Many researches attempt to address this issue by increasing the water and cement content in order to achieve the required workability at a constant water to cement (W/C) ratio [15, 16]. However, higher cement content can affect the properties of the hardened concrete like shrinkage besides being not economical.

Considering these issues, samples of recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) were made separately with the same amount of cement and consistence. The NA used for preparation of reference concrete is typically industrial gravel. It is a quaternary postglacial river gravel which was partially mechanically crushed (regionally available in Poland and in different European regions with a glacial history). Petrographically it is a mix of different sandstones, granite, quartzite and small amounts of dolomites and porphyries. Water absorption of this NA is 1.8% compared to 5.4% for RA.

Based on initial concrete recipes, fresh concrete mixes were prepared with a laboratory mixer (18dm^3), and afterward the properties of the first fresh concrete mixes were used as basic information for modification of concrete recipes. The modified concrete recipes for both RAC and NAC can be seen in Table 2-7. Curing condition after de-moulding of samples was according to EN 12390-2. Figure 2-10 shows the compressive strength with the standard errors resulting from the tests done in triple. Fresh and hardened concrete properties can be seen in Table 2-8.

Table 2-7: Modified mix composition of RAC and NAC.

Component	RAC		NAC	
	Mass [kg]	Volume [dm^3]	Mass [kg]	Volume [dm^3]
Cement – CEM I 42.5R	380	123	380	123
Water	167	167	137	137
Coarse	1162	445	1063	439
Sand	508	192	603	227
Superplasticizer	0.8% of cement mass			
Air entraining admixture	0.4% of cement mass			
Initial W/C ratio	0.44		0.36	

Table 2-8: properties of fresh and hardened concrete.

Type of concrete	Fresh concrete		Hardened concrete	
	Slump(mm)	Air content Vol.%	Abrasion resistance (mm)	water absorption [% wt.]
NAC	130	6.5	22.5	5.7
RAC	140	6.5	23	6.4

Considering Figure 2-10, it is clear that recycled aggregate concrete achieved more compressive strength up to 30% at early ages and after aging this difference has become lower, to 5% at 90 days.

For normal concrete with typical aggregate the interfacial transition zone (ITZ) is composed of three layers: a film composed of a sub-layer of Ca $(OH)_2$ in direct contact with aggregate surface and C-S-H sub-layer with ettringite crystals backing it, large portlandite crystals and porous layer which are smoothly dense to normal bulk C-S-H paste. The thickness of this zone is different, usually about 30-100 μm [17]. This special structure of ITZ is a result of higher local water/cement ratio in the vicinity of aggregate surface because of wall effect. Also water which is absorbed on the aggregate surface plays an important role in this phenomenon. In comparison with natural aggregates, CDW aggregates usually are more porous. From this the ITZ microstructure of the concrete with the addition of recycled aggregates are different

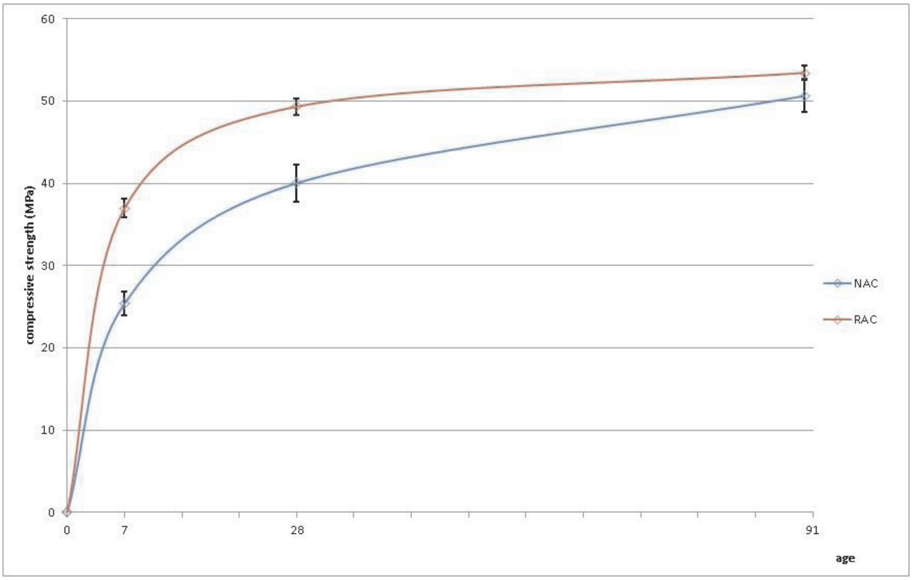

Figure 2-10: Comparison between compressive strength of NAC (—) and RAC (—) in different ages.

from that of the concrete with natural aggregates. In the fresh concrete mix made with recycled aggregates the high porosity and water absorption capacity of these aggregates, usually coupled with its low initial water content, rendered the aggregate to take up a large amount of water during the initial mixing stage and lowered the initial W/C ratio in the ITZ at early hydration.

Newly formed hydrates gradually filled this region. This process effectively improved the interfacial bond between the aggregate and cement, what could result in growing early strength development of the concrete. Additionally, in comparison with natural aggregates, CDW aggregates are usually partially carbonated on the aggregates surface (old mortar or cement paste) what could increase growing of new hydration products in the initial time of hydration[18]. According to earlier research, the compressive strength of recycled aggregate concrete is usually lower (in some cases up to 20% lower) compared with the strength of control mixes [15]. Hansen et al. made different strength class of recycled aggregate and applied them into new concrete again [19]. In their experiments, all recycled aggregate concretes were made with coarse recycled aggregate and natural sand. Among their results it can be seen that RAC made with coarse recycled aggregate and natural sand obtained approximately the same strength and in some cases higher strength than NAC. Also if the W/C of the original concrete is the same as or lower than that of the RAC, then the strength of RAC can be as good as or higher than the strength of the original concrete [20].

Results of the compressive strength of RAC made of ADR coarse product is in agreement with mentioned research. An experimental study was performed in accordance with PN-B/88-06250 to check durability of RAC and NAC. Twelve cube samples with a size of 100*100*100 mm were stored for 56 days under the condition with relative humidity greater than 95% (water) and at a temperature of 20°C ± 2°C. After 56 days of ageing, 6 samples were placed in water with a temperature of 20°C ± 2°C while the remaining six samples were subjected to cycles of freezing and thawing at a rate of 2–3 cycles per day. Freezing took place in air (-18°C ± 2°C) and thawing in water (18°C ± 2°C). Frost resistance was determined by a drop in compression strength and a loss of mass in the samples subjected to cyclic freezing compared to the control samples which were stored in water at 20°C. After 100 cycles, compressive strength and weight loss of samples were determined. According to the standard, frost resistant concrete should have a mass loss of less than 5% and a loss of compression strength smaller than 20%. Results show that NAC had a reduction in compressive strength of 0.6%, and loss of weight below 5%. Simultaneously, RAC samples showed a decrease in compressive strength of 10.4%, and loss of weight below 5%. Considering PN-B/88-06250 both concretes fulfil requirements for F100 class of freeze-thaw resistance (see Table 2-9). Differences in compressive strength after cycles of freezing and thawing between RAC and NAC could result from many factors, e.g. the higher water absorption of recycled aggregates, mineralogical types of aggregates, porosity and concrete recipe parameters like: W/C ratio, air content.

Table 2-9: Compressive strength of samples after freeze-thaw cycle and control samples in water.

Type of concrete	Compressive strength (MPa) control samples in water	standard error (+/-)	compressive strength (MPa) after freeze-thaw cycles	standard error(+/-)	Loss of weight [%]
NAC	61.9	1.3	61.5	1.2	< 5
RAC	56.4	0.5	50.6	1.6	< 5

2.6 CONCLUSION

A new process is being developed in the context of the European C2CA project, which aims to reduce the environmental impact of Construction & Demolition waste by in-situ mechanical recycling of EOL concrete into high-grade aggregate and low- CO_2 raw material for cement. The process applies autogenous milling and ADR to extract 4-16 mm recycled aggregate from crushed concrete.

Among the various mechanical liberation routes, attrition milling at low to medium compression appears to produce aggregate of particularly high quality. This type of attrition milling offers low-complexity (mobile) and low-cost technology. After milling, ADR efficiently separates the moist material into fine and coarse fractions. In the course of the first demonstration case of the new technology, recycled aggregate was tested into new concrete (RAC) to investigate the workability, compressive strength and durability compared to concrete made from natural aggregate. The RAC showed 30% higher compressive strength after 7 days. It is believed that the favorable development of strength of the recycled aggregate is caused by changes in the surface of the particles as a result of the intensive liberation process. The results of the freeze-thaw resistance showed that the recycled concrete performed less well than NAC but fulfilled the requirements for F100 class.

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CHAPTER 3

Performance of RAC based on the type of cement and RA substitution

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This chapter is based on the published article:
Lotfi S, Eggimann M, Wagner E, Mróz R, Deja J, Performance of recycled aggregate concrete based on a new concrete recycling technology, Construction and Building Materials, 95 (2015) 243-256.

3.1 ABSTRACT

This part concentrates on the second demonstration project of C2CA, where EOL concrete was recycled on an industrial site. After recycling, the properties of the produced Recycled Aggregate (RA) were investigated, and results are presented. An experimental study was carried out on mechanical and durability properties of produced Recycled Aggregate Concrete (RAC) compared to those of the Natural Aggregate Concrete (NAC). The aim was to understand the importance of RA substitution, w/c ratio and type of cement to the properties of RAC. In this regard, two series of reference concrete with strength classes of C25/30 and C45/55 were produced using natural coarse aggregates (rounded and crushed) and natural sand. The RAC series were created by replacing parts of the natural aggregate, resulting in series of concrete with 0%, 20%, 50% and 100% of RA. Results show that the concrete mix design and type of cement have a decisive effect on the properties of RAC. On the other hand, the substitution of RA even at a high percentage replacement level has minor and manageable impact on the performance of RAC. This result is a good indication towards the feasibility of using RA in structural concrete by modifying the mix design and using a proper type of cement.

3.2 INTRODUCTION

Construction and Demolition Waste (CDW) is one of the heaviest and most voluminous waste streams generated in the EU. It accounts for approximately 40% of all waste produced in the EU and consists of numerous materials, including concrete, bricks, gypsum, etc. which can be recycled[1]. According to the revised Waste Framework Directive, the minimum recycling percentage of 'non-hazardous' CDW, should be at least 70% by weight until 2020, while the current average recycling rate of CDW for EU-27 is only 47%[2].

By recycling part of the concrete fraction of CDW into high-quality construction materials like aggregate and cement for new concrete, it is possible to take advantage of the surplus of waste. There has been vast research to solve associated problems with End of Life (EOL) concrete[4-8]. However, it should be noticed that due to the low price of concrete also the overall cost of the recycling process, the implemented concrete recycling route should be economically beneficial and environmentally sustainable.

A new technology of concrete recycling called C2CA (Concrete to Cement and Aggregate) aims at a cost-effective system approach for recycling high-volume EOL concrete streams into prime-grade aggregates and cement (see Figure 3-1)[3].

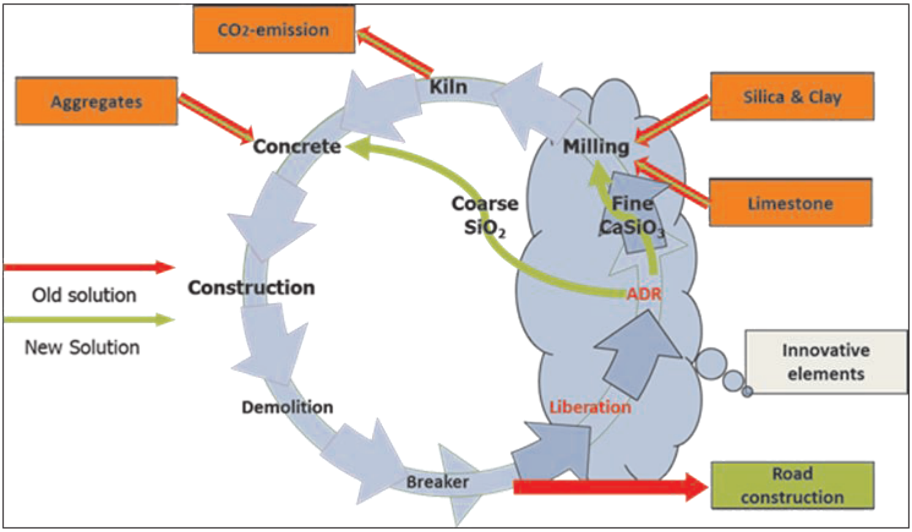


Figure 3-1: C2CA concrete to concrete recycling process.

In C2CA, after crushing of EOL concrete, autogenous milling is used to remove the loose mortar from the surface of the aggregates. The removal of the loose mortar is mentioned to be one of the key points to improve the mechanical strength of the RA[4]. After autogenous milling, a new low-cost classification technology, called Advanced Dry Recovery (ADR) is applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles. ADR is a key technology in C2CA. It uses kinetic energy to break the bonds that are formed by moisture and fine particles and can classify materials almost independent of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product and a fine fraction that includes the cement paste and contaminants such as wood, plastics and foams[9,10]. Figure 3-2 schematically shows the ADR principle.

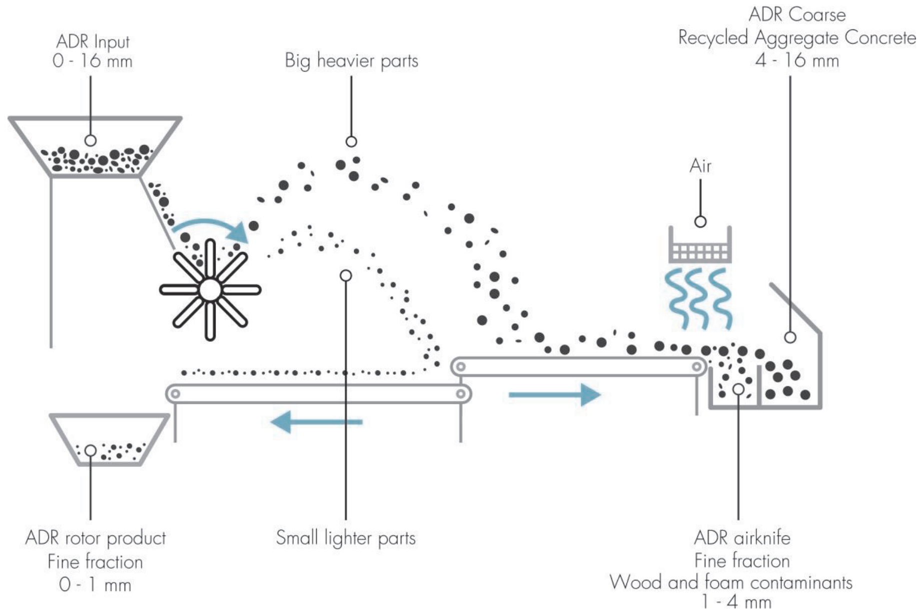


Figure 3-2: Schematic of the ADR principle.

One of the major goals of the project, next to in situ processing and local reuse of the aggregate, is to help decrease CO_2-emissions in cement production by concentrating part of the cement paste from EOL concrete into a separate fraction that can be reused as a low- CO_2 feedstock replacing primary limestone. Already in 2000, world cement production amounted to 8.6% of global CO_2-emissions from fossil fuels[11]. The present chapter accounts for the report on the re-use of recycled coarse aggregate produced via C2CA process. In spite of the availability of considerable research in this field[12-18], most of the existing information is not comparable due to the heterogeneity of the recycled aggregates, applied concrete mix designs and production. This chapter includes all information regarding the concrete recycling process, properties of Recycled Aggregate (RA), and mechanical and durability properties of concrete using different RA substitution rates and different w/c ratios.

3.3 MATERIALS AND METHODS

3.3.1 Concrete recycling process

The concrete recycling was performed based on the C2CA process. Technologies that are smart dismantling and demolition, crushing, autogenous milling, and ADR processing were applied respectively[3]. EOL concrete originated from two governmental towers that were used as case study for the C2CA project. For this trial, a mill

(5.6 meter length, 2.2 meter diameter and 12RPM speed) with a maximum internal capacity of 16 tons was installed on site. Milling of materials was carried out followed by screening at 16 mm and an ADR with a maximum capacity of 120 tons per hour. Figure 3-3 shows the concrete recycling process. It shows that ADR at the end delivers two main products: Coarse (4-16mm) and fines (0-4mm). In this study, ADR coarse product was used for the concrete production.

3.3.2 Concrete production

Laboratory tests were conducted on the ADR coarse product to evaluate the properties of RA. A concrete production trial was carried out to study the fresh, hardened and durability properties of Recycled Aggregate Concrete (RAC). Two series of concrete, were produced: C1, corresponding to C25/30 S3 D16 (produced by Holcim) and C2, corresponding to C45/55 S3 D16 (produced by HeidelbergCement).
For all mixes, rounded Natural Sand (NS) was used. Two types of natural coarse aggregate "Natural Rounded (NR) and Natural Crushed (NC)" were utilized for reference concrete production (without RA). RAC with 20%, 50% and 100% of RA substitution was produced. Physical properties of natural aggregates and sand can be seen in Table 3-1. Table 3-2 shows the mix designs of C1 and C2. CEMI (OPC) used in concrete series C2, is produced using ADR fines. RA substitution percentage in both C1 and C2 was varied from 0% to 100% (see Table 3-3). Superplasticizer (polynaphthalene sulfonate based liquid admixture) was dosed to concrete C2 series to achieve the targeted consistency of S3 (125 +/- 25 mm slump). After the mixing procedure and filling the molds, samples were cured according to EN 12390-2. For each concrete series (C1 and C2), comparative concrete samples with the same mix design but inverse type of cement were produced. The aim was investigating the impact of cement type on some durability properties of concrete samples.

Table 3-1: Physical properties of natural aggregate and natural sand.

Properties	NR	NC	NS
Density[kg/m3]	2610	2790	2620
Water Absorption[wt.%]	1.2	1.5	0.8

Figure 3-3: Concrete recycling process.

Table 3-2: Composition of concrete in mixtures series C1 and C2.

Serie	Cement [kg/m³]	w/c ratio	Water [kg/m³]	Plasticizer	Air entrainer	Consistency Class	Aggregate grading	Concrete Class	Type of coarse aggregate *
C1	300 CEM III/B 42.5	0.60	180	-	none	S3	DIN A-B/16 mm	C25/30 S3 D16	NR, NC, RA
C2	340 CEM I 52.5R	0.45	153	1.2%	none	S3	DIN A-B/16 mm	C45/55 S3 D16	NR, RA

Table 3-3: Recycled aggregate substitution percentage and type of natural coarse aggregates in C1 and C2.

C1 series with CEMIII/B 42.5 (Holcim)

Variables	*No Natural Agg*	*Natural rounded aggregate (NR)*			*Natural crushed aggregate (NC)*		
	100% RA	*100%Round 0% RA*	*80%Round 20%RA*	*50%Round 50%RA*	*100%Crushed 0%RA*	*80%Crushed 20%RA*	*50%Crushed 50%RA*
Natural Aggregate		C1NR_Ref			C1NC_Ref		
Recycled Aggregate(RA)	C1_RA100%		C1_NR_RA20%	C1_NR_RA50%		C1_NC_RA20%	C1_NC_RA50%
Comparitive sample with CEM I		C1NR_CEM I_Ref					

C2 series with CEMI 52.5 R (HeidelbergCement)

Variables	*No Natural Agg*	*Natural rounded aggregate (NR)*			*Natural crushed aggregate (NC)*		
	100% RA	*100%Round 0% RA*	*80%Round 20%RA*	*50%Round 50%RA*	*100%Crushed 0%RA*	*80%Crushed 20%RA*	*50%Crushed 50%RA*
Natural Aggregate		C2NR_Ref					
Recycled Aggregate(RA)	C2_RA100%		C2_NR_RA20%	C2_NR_RA50%			
Comparitive sample with CEM III		C2NR_CEM III_Ref					

3.3.3 Performed Experiments

Table 3-4 shows the list of tests and corresponding standards for determining the properties of RA, also fresh and hardened properties of RAC and Natural Aggregate Concrete (NAC).

Table 3-4: Test methods used for determining fresh and hardened properties of concrete and recycled aggregate.

Test	Standard
RA testing	
Density SSD[kg/m3]	EN 1097-6
Water Absorption[wt.%]	EN 1097-6
Los Angeles index[wt. %]	EN 1097-2
Flakiness index	EN 933-3
Resistance to crushing[wt. %]	PN-B-06714-40
Resistance to Freezing and Thawing[wt. %]	EN 1367-1
RAC and NAC testing	
Slump	NEN-EN 12350-2
Air content, fresh concrete density	NEN-EN 12350-6
Compressive strength	NEN-EN 12390-3
Porosity and Water permeability	SIA 262/1-A
Permeability of concrete to oxygen	Rilem Cembureau Method
Abrasion resistance	(EN-1338)
Accelerated carbonation	Polish National Standard
Freeze/thaw resistance	DIN CEN/TS 12390-9
Rapid Chloride migration	NT BUILD 492
Two electrodes method	CUR C177

3.4 RESULTS AND DISCUSSION

3.4.1 ADR input and outputs

The performance of ADR was evaluated by sampling and analysing of all ADR products. The moisture content and particle size distribution of ADR input and outputs were determined (Table 3-5). It is clear that the moisture is mostly associated with the fine fraction. By removing this portion, the originally sticky material becomes loose and processable. ADR fine fractions are called air-knife and rotor products. Air knife product has the highest wood content compared with other products. Particle size distributions of ADR input and three outputs are shown in Figure 3-4.

Table 3-5: Moisture content of ADR input and outputs.

Moisture content of samples				
unit	ADR input	recycled coarse aggregate	recycled fine (air knife)	recycled fine (rotor)
Mass%	6.9%	5.5%	10.0%	11.6%

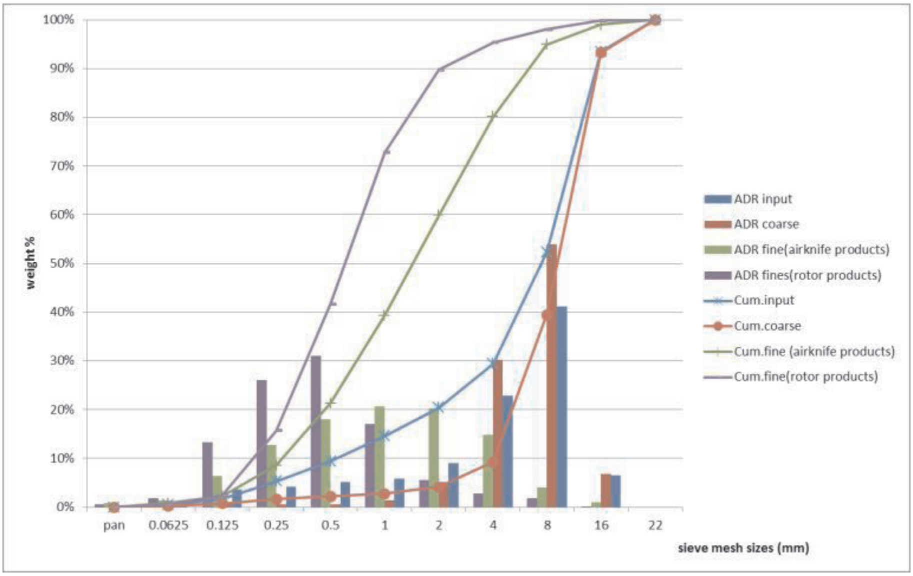


Figure 3-4: Particle size distribution of ADR input and outputs. The lines show the cumulative curves whereas the bars indicate the absolute fraction weights.

3.4.2 Properties of RA

Table 3-6 shows some physical and mechanical properties of RA measured at AGH University. The guideline prepared by RILEM recommends recycled coarse aggregates for concrete production if their water absorption is between 3% and 10%[19]. According to recommendations of an international committee, coarse RA having water absorption capacity more than 7% is not desirable to be used in concrete[18]. The value obtained for RA in this study corresponds well with this recommendation. Los Angeles abrasion index is a parameter used to measure resistance of aggregate to fragmentation. Because of the adhered mortar, sometimes RA has higher Los Angeles coefficient value than natural aggregate (NA)[20,21]. The mass percentage of adhered mortar on fractions 4-8mm and 8-16mm was determined using acid treatment method reported in[22] (see Figure 3-5) . Table 3-7 validates the fact that higher amount of adhered mortar is concentrated in the finest fraction. The amount of adhered mortar is in line with the literature[18, 23]. It should be considered that the existence of the natural limestone aggregate could lead to an overestimation during the acid treatment[24].

Table 3-6: General properties of recycled aggregate (reported by AGH)

Density SSD[kg/m3]	2424
Water Absorption[wt.%]	6.1
Los Angeles index[wt. %]	59.8
Flakiness index	5.1
Resistance to crushing[wt. %]	14.1
Resistance to Freezing and Thawing[wt. %]	11.2

Table 3-7: Adhered mortar in recycled aggregates

Fraction[mm]	Natural aggregate[wt.%]	Adhered mortar[wt.%]
4-8mm	47%	53%
8-16mm	60%	40%

3.4.3 Properties of fresh concrete

The use of RA has an important effect on concrete workability. The high and inconsistent water absorption of RA (5.6 wt.% and 8.8 wt.% reported by HeidelbergCement and Holcim respectively) influences the “effective mixing water” and thus makes it difficult to adjust and control the slump of concrete. The two concrete series with different w/c allow studying the sensitivity to the water content, and consequently the impacts on the mechanical and durability properties of hardened concrete. Table 3-8 shows the fresh properties of the concrete mixtures. C1 mixtures show higher slump at 5 and 60 minutes. In C2 series, the maximum allowed superplasticizer dosage of 1.2% was applied, but for some mixes this was not sufficient to achieve the target slump. In series C1, the use of crushed aggregates (NC) reduces the slump compared to the mixes with NR aggregate. Unlike with the C1 mixes, the concretes of the C2 series show a decrease of workability with increasing RA replacement. In C2 series, the observed slump reduction with increasing RA replacement reflects the real workability loss due to the challenging aggregate properties (see correlations in Figure 3-6). In C1 series, the high w/c ratio most likely prevents to observe this trend. Considering Figure 3-7, fresh density of recycled aggregate concrete in all series decreases by increasing substitution rate of RA. The reason is due to the additional porosity introduced by RA which also causes higher water absorption. A good correlation between air content and fresh density in C1 series is observed.

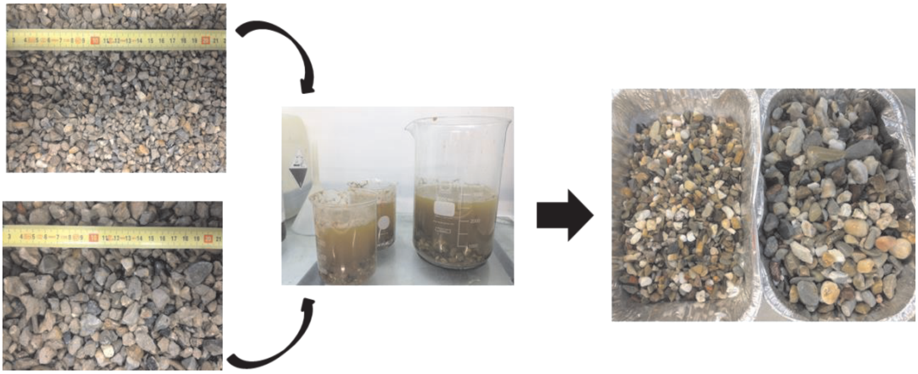


Figure 3-5: Immersing 4-8mm and 8-16mm RA into acid and washing on 4mm sieve to determine the mortar content.

Table 3-8: Fresh properties of concrete mixtures.

Concrete code	RA-replacement	Slump 5'	Slump 60’	Fresh density 5'	Air content 5'
	[%]	[mm]	[mm]	[kg/m^3]	[%]
C2NR_Ref	0	150	34	2370	2.3
C2_NR_RA20%	20	151	37	2350	2.6
C2_NR_RA50%	50	106	29	2320	2.1
C2_ RA100%	100	78	10	2280	1.8
C2NR_CEMIII_Ref	0	224	207	2380	1.0
C1NR_Ref	0	190	170	2345	0.9
C1_NR_RA20%	20	240	230	2279	1.2
C1_NR_RA50%	50	220	210	2279	1.2
C1_RA100%	100	240	220	2200	1.7
C1NC_Ref	0	175	145	2396	1.2
C1_NC_RA20%	20	190	160	2355	1.4
C1_NC_RA50%	50	215	190	2297	1.4
C1_RA100%	100	240	220	2200	1.7
C1NR_CEM I_Ref	0	180	130	2340	1.5

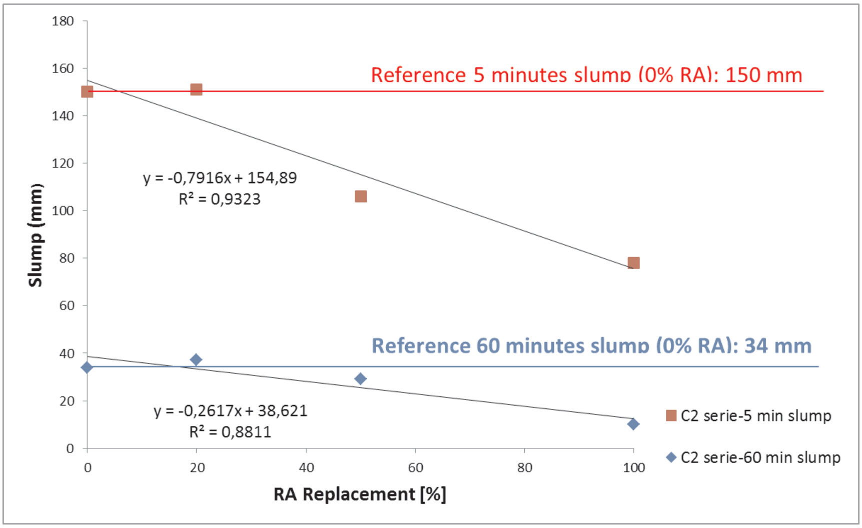


Figure 3-6: Effect of RA replacement on 5 and 60 minutes slump for concrete series C2.

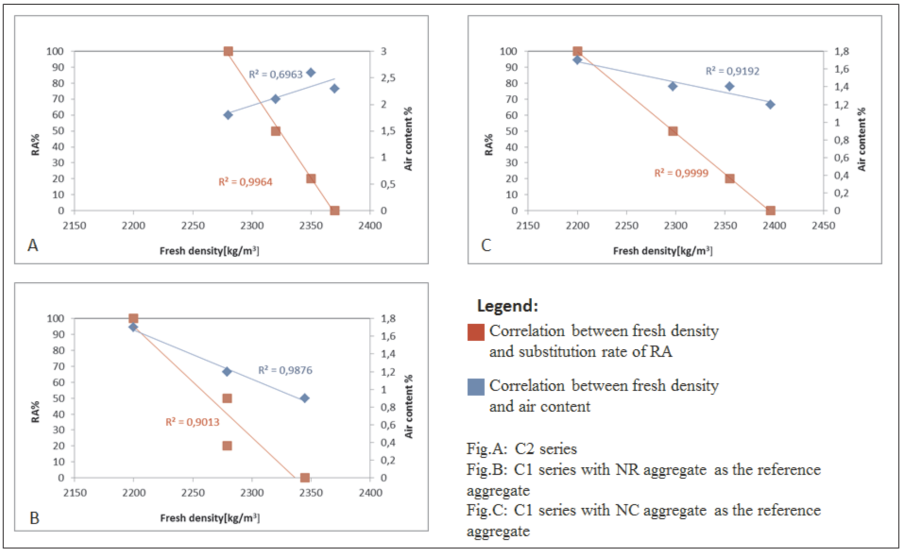


Figure 3-7: Correlation between RA%, Fresh density and air content in concrete series (data points are related to the concrete samples with different RA%).

3.4.4 Properties of hardened concrete

3.4.4.1 Compressive Strength

The measured compressive strength of concrete corresponds well to the two targeted concrete classes. Because of the low w/c and the CEM I used for C2 series, the compressive strength already reaches around 40 MPa after two days (Figure 3-8-top). The results show a slight loss in compressive strength with increasing RA replacement in C2 series. However, compressive strength loss in C1 series is higher. The influence of recycled aggregate could be more negative for concretes with high w/c[25]. It is reported that the loss of compressive strength due to the incorporation of RA is less for mixes with higher targeted compressive strength (45 and 65 Mpa) compared to mixes with lower targeted compressive strength (20Mpa)[26]. This is in line with the outcome of the current study where the maximum loss of strength for 28 days samples in C2 series is 12% compared to 23-33% in C1 series. Considering Figure 3-8 (bottom and middle) in C1 mixes, compressive strength of concrete made of NC is slightly higher than the compressive strength of samples made of NR. A rougher texture of aggregates results in a greater adhesive force between the particles and the cement matrix[27].

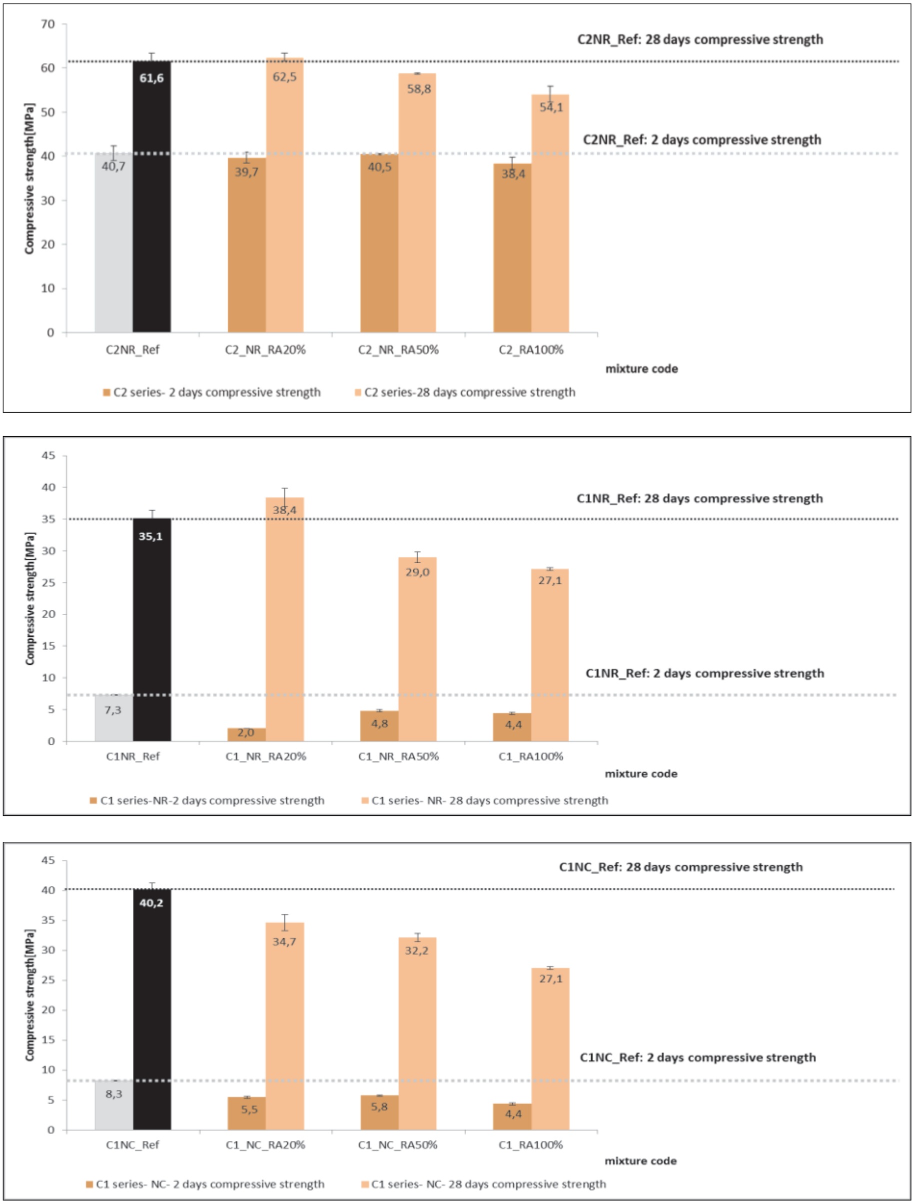


Figure 3-8: 2 and 28 days compressive strength- top: series C2 with NR aggregate, middle: series C1 with NR (Natural Rounded), bottom: series C1 with NC (Natural Crushed) aggregate.

3.4.4.2 Porosity and Water permeability

Considering Figure 3-9 the porosity of RAC is higher than that of NAC. By increasing RA substitution and w/c ratio, the porosity of samples increases clearly. Adhered mortar present in recycled aggregate has weak and porous structure and increases the porosity of RAC[28,29]. Porosity is one of the main characteristics of concrete which affects the permeation of foreign substances[30,31]. Results of the water permeability test are presented in Figure 3-10. Comparing Figure 3-9 and Figure 3-10, it is obvious that higher porosity results in higher water permeability. Results show that the permeability of concrete increases with increasing RA content, as reported previously[32]. However, the effect of the w/c ratio on water permeability is more dominant (see comparative mixes in Figure 3-10). The rate of most kinds of concrete deterioration depends on concrete permeability. This is because water absorption is indirectly related to permeability of hardened concrete, and penetration of water into concrete is required for most deterioration mechanisms to be effective[33]. According to the results, adverse effect of RA on porosity and water permeability of RAC is minimized using less water in concrete mixture.

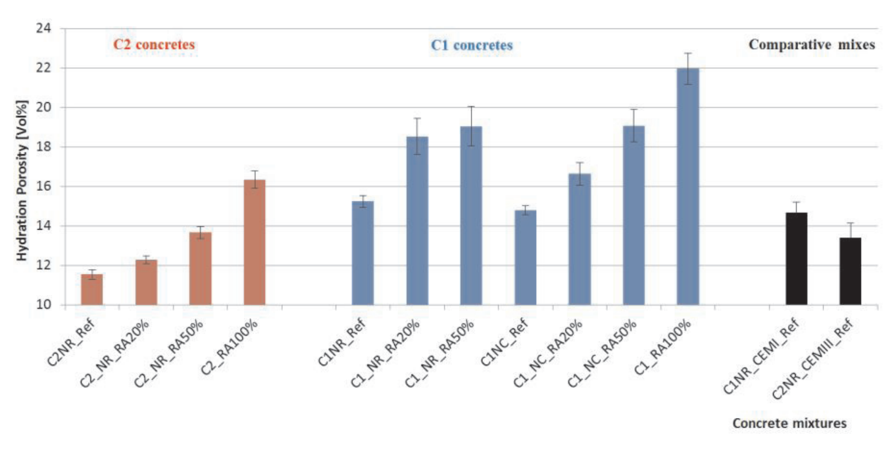


Figure 3-9: Hydration prorosity of concrete samples.

3.4.4.3 Oxygen Permeability

The Oxygen permeability coefficients for different concrete samples are given in Figure 3-11. Results show that oxygen permeability is mostly influenced by the concrete mix design. But also the replacement of natural aggregates with recycled aggregates increases the Oxygen permeability. The comparative mixes indicate that concretes made with CEM I yield to a lower Oxygen permeability than concretes with CEM III. Considering the aggregate type, the lowest permeability is achieved with rounded, natural aggregates. Crushed aggregates show significantly higher values. However, it does not matter if the crushed aggregate is natural (crushed rock) or recycled. Oxygen permeability of C2 series is still within the accepted range of conventional concrete that is not exposed to aggressive environment (10^{-18}- $10^{-17}m^2$)[34].

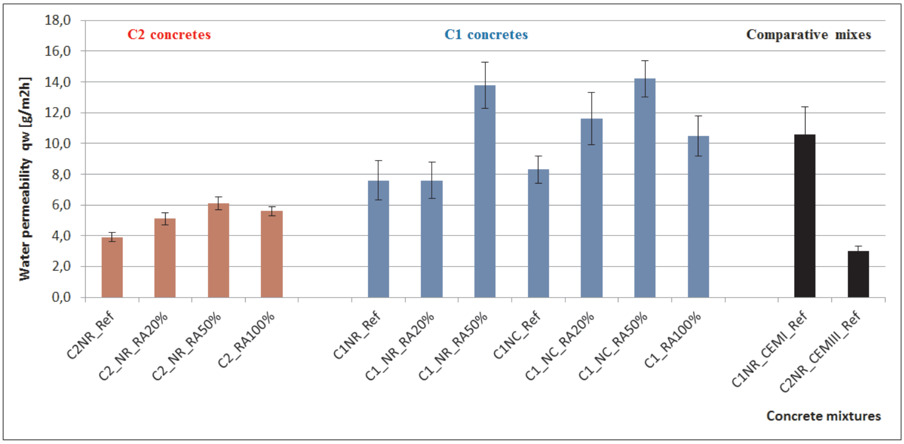


Figure 3-10: Water permeability of concrete samples.

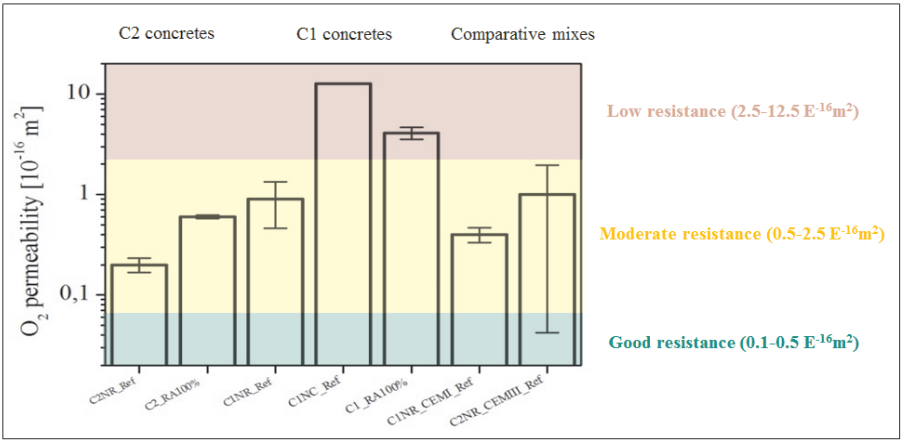


Figure 3-11: Oxygen permeability of concretes containing 100% ADR aggregates and reference mixes.

3.4.4.4 Carbonation resistance

The depth of carbonation in concrete samples, under controlled exposure conditions is shown in Figure 3-12. Considering the results and regardless of the mix design, carbonation depth increases by increasing the replacement of RA. C2 concretes presented a better carbonation resistance in comparison to C1 concretes (see Figure 3-13). The low w/c ratio in C2 series enhances durability due to creating a much denser matrix. It is known that the use of superplasticizer improves the carbonation performance of concrete, since it leads to a reduction of the effective w/c ratio, which results in a decrease of porosity and CO_2 permeability[35]. The carbonation depth achieved in C2 series corresponds well with the results reported by Soares et al. where concrete samples are made of RA besides superplasticizer[35]. Pedro et al. reported that the carbonation depth increases with the decrease of the concrete's target strength[26]. This trend can be seen as well in the current study. According to the comparative mixes in Figure 3-12, it is concluded that the depth of carbonation of CEMIII concrete is higher than the equivalent strength-grade concrete containing CEMI, this fact was already observed in another study[15]. During hydration of CEMI the amount of produced calcium hydroxide is higher in comparison with CEM III (pH buffering capacity higher) and this is a major reason for achieving better resistance to the carbonation for C2 series. According to[25], the main factor affecting the carbonation of the RAC is the alkalinity, although a crucial factor is the permeability of concrete[36]. It should also be noticed that systems with slag cements hydrate slower compared to systems containing ordinary Portland cement. This leads to densification of the microstructure and better durability of slag-systems at later ages. Considering data for reference samples and samples with 100% RA replacement, a good correlation was found between carbonation depth, compressive strength and water permeability (see Figure 3-14).

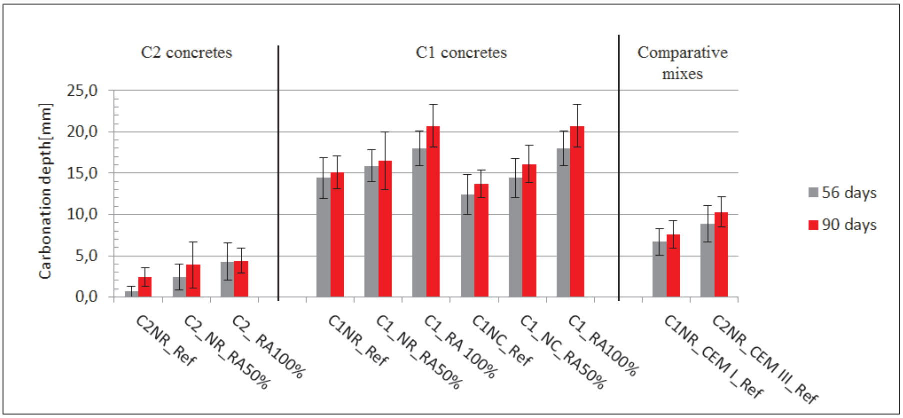


Figure 3-12: Carbonations depth after 56 and 90 days

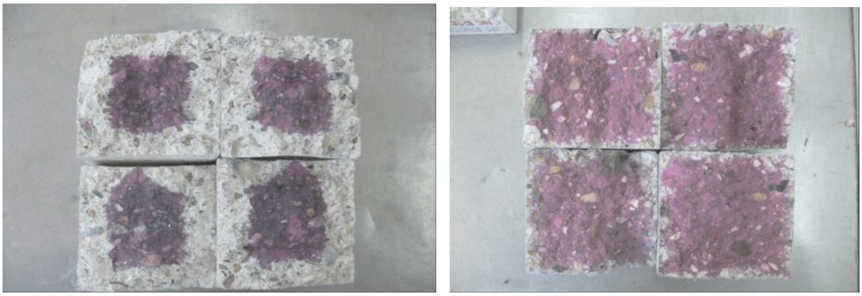


Figure 3-13: The impact of concrete mix design on carbonation depth (white parts of the concretes). Left: C1mix design; Right: C2 mix design. Both concretes contain 100% ADR aggregate.

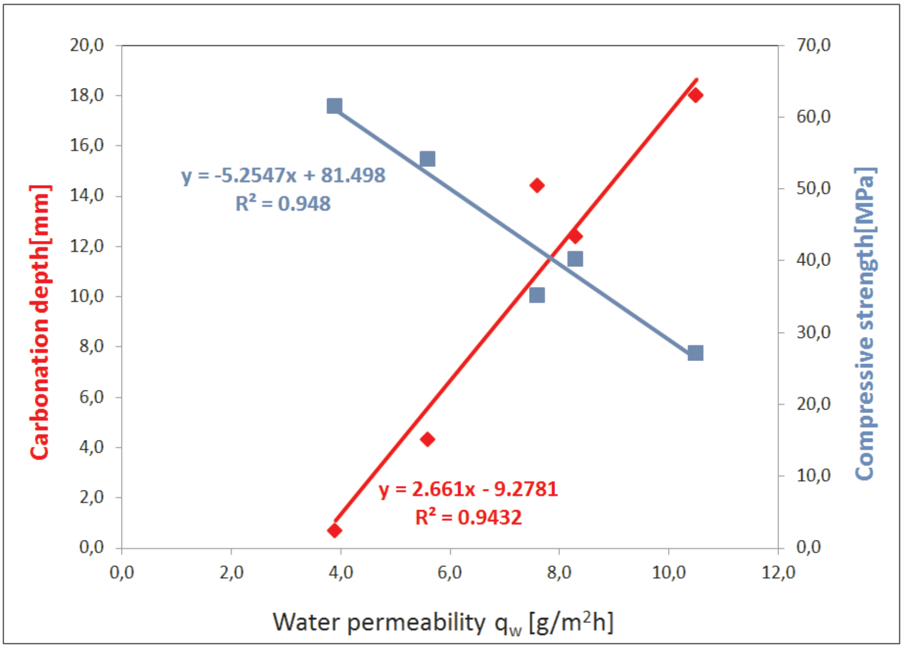


Figure 3-14: Correlation between water permeability and carbonation and water permeability and compressive strength (data points are related to the reference samples with natural aggregate and samples made of 100% RA substitution).

3.4.4.5 Freeze-thaw resistance

The freeze-thaw resistance test was carried out on reference concrete samples and concrete specimens with 100% RA replacement. For this test, all samples were produced using air entraining agent (Sika LPS A 94) in order to get the targeted air content of 4.5±0.5%. The results of CIF tests (without de-icing salt) for C1 and C2 concrete samples can be seen in Figures 3-15 and 3-16. Weight loss in concrete with CEMIII/B and a high w/c of 0.6 (C1 series) is strongly influenced by the type of aggregates comparing to the reference concrete with natural aggregates. Considering Figure 3-15, in C1 series only reference concrete stays below the limit value. On the other hand, the C2 concrete series with CEMI and lower w/c of 0.45 with or without RA are not much affected by freeze-thaw cycles. This significant difference in the freeze-thaw behaviour of the two examined concrete mix designs can be related to the compressive strength and density of mixes. In Figure 3-16 changes in E-Modulus of concrete samples under freeze-thaw condition can be observed. Based on the results, concretes with higher strength classes and higher 28 days compressive strength (as it is in C2 series) seem not to be affected by use of recycled aggregates even at 100% replacement level of RA. For concrete with low compressive strength (less than 30MPa at 28 days), and according to the results from C1 series, full replacement of natural aggregates with recycled one is not recommended. Although, in some research it is reported that there is no significant difference in frost resistance of RAC and NAC and in many cases recycled mixes tested exhibited better durability than concrete made with virgin materials[37].

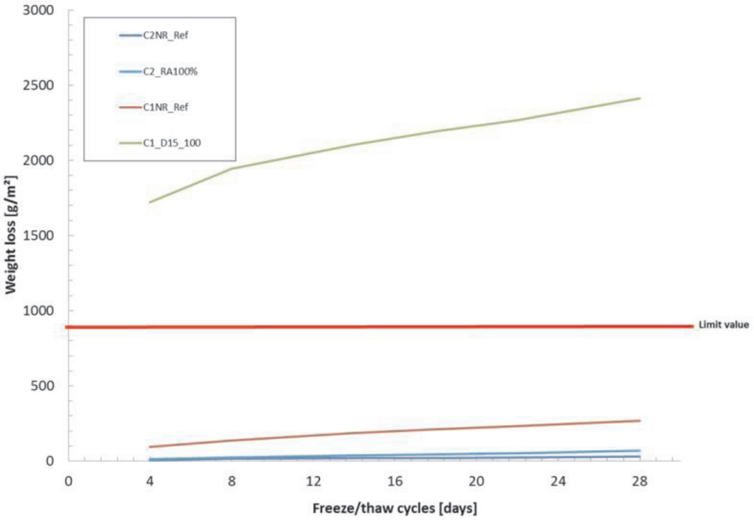


Figure 3-15: Scaling of C1 and C2 concrete samples with 100% RA and 100% NA, under freeze-thaw cycles up to 28 days.

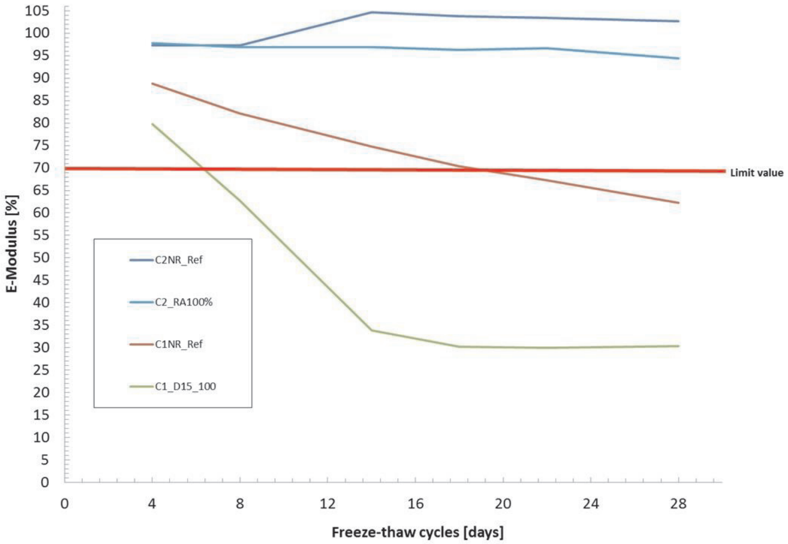


Figure 3-16: E-modulus of C1 and C2 concrete samples with 100% RA and 100% NA, under freeze-thaw cycles up to 28 days.

3.4.4.6 *Rapid chloride migration*

Chloride ions affect the durability of concrete subjected to the action of sea water, marine areas and de-icing salts. The penetration of chloride ions can cause corrosion of concrete and rebars embedded in concrete. Corrosion of concrete is caused by expansive products obtained in the reaction of chloride ions with components of concrete and mainly $Ca(OH)_2$, e.g. expansive alkaline calcium chloride $Ca(OH)_2$. H_2O. $CaCl_2$, which increases its volume during crystallization and causes destruction of concrete[38]. In order to quantify the chloride ingress speed in concrete, the chloride diffusion or coefficient is used, because the diffusion controls the ingress of chlorides[39]. The Rapid Chloride Migration (RCM) test, described in the guideline NT Build 492[40], is one of the accelerated test methods, which is nowadays very often used[39]. For this test, an external electrical potential is applied axially across the specimen and forces the chloride ions outside to migrate into the specimen. The chloride penetration depth can then be measured from the visible white silver chloride precipitation[40]. According to the Figure 3-17 chloride migration in C2 concretes is higher than that in C1 concretes. CEM I (C2 concretes) causes higher pH than CEM III (C1 concretes) due to the higher content of $Ca(OH)_2$. As the consequence of the higher OH^-activity, the electrical conductivity is higher with CEM I than with CEM III. This increases the electrical current passing through the concrete and therefore increases the migration of Cl^-.

For C1 concretes, all results are below the limit level indicating good resistance to chloride diffusion. Most of the C2 concretes show values above the limit ($10\cdot10^{-12}m^2/s$), indicating a poorer resistance to chloride diffusion. In general the resistance to chloride ion penetration decreases as the recycled aggregate content increases, and this is seen in other research[28]. The type of aggregates has no significant impact on chloride migration as chloride migration is mainly dominated by the cement type.

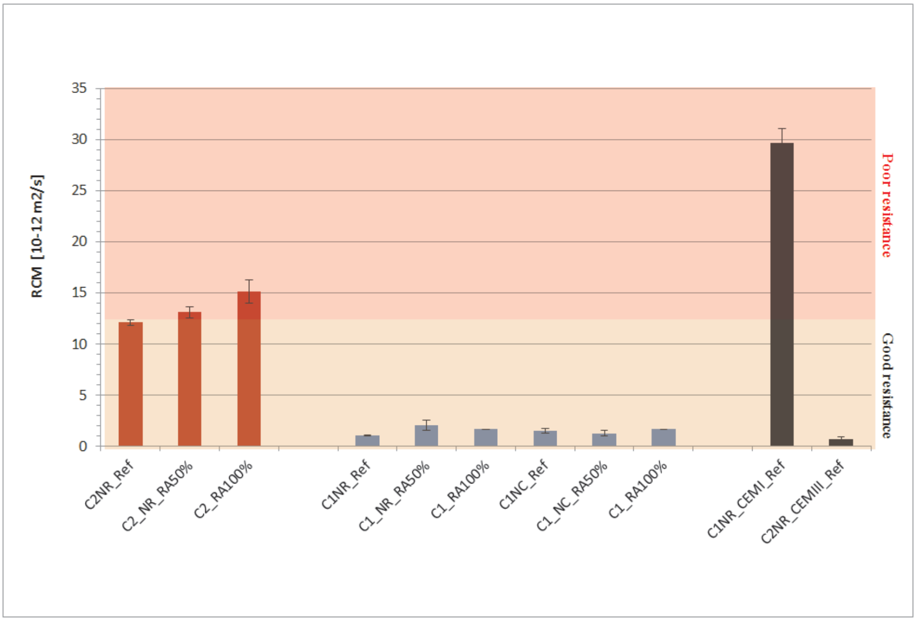


Figure 3-17: Rapid chloride migration data of the series C1 and C2 concretes.

3.4.4.7 Two electrodes method (TEM)

The electrical resistance of concrete can be measured by applying current using two electrodes attached to the end of a uniform cross-section specimen. The results of TEM clearly discriminate the two concrete mix designs (Figure 3-18). C1 series show a higher electrical resistance than C2 concretes. However, there is no systematic impact of the various types of aggregate. The comparative mixes demonstrate that the cement type has a substantial impact on the measured resistance. The mix design (w/c and aggregate type) seems to have a minor impact, and the method is not sensitive enough to distinguish the effect of the kind of aggregate.

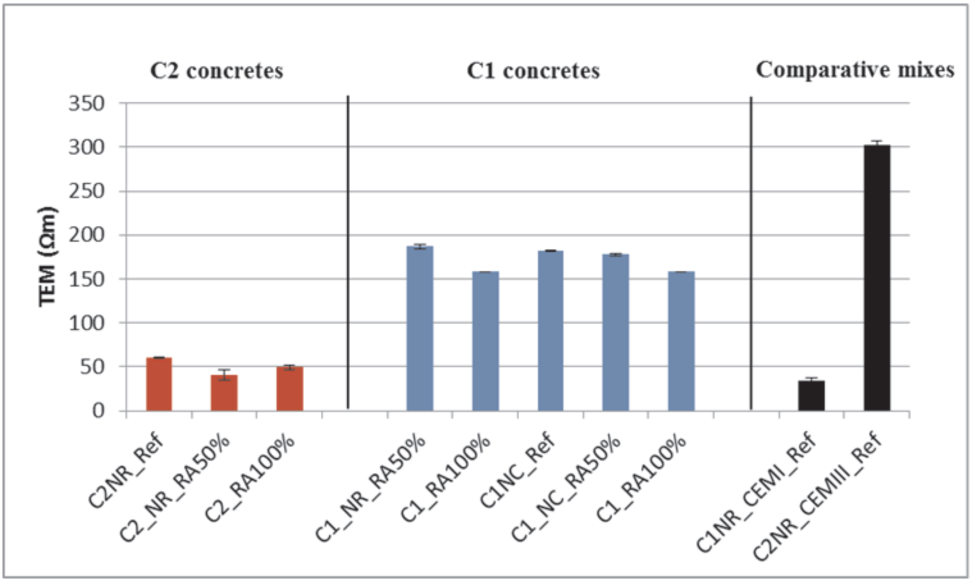


Figure 3-18: Electrical resistance of concrete samples.

3.4.4.8 Abrasion resistance

In order to determine the concrete abrasion resistance, the wide wheel method according to EN-1338 was used. In this way, a steel disc of 200mm diameter and 70mm width is rotated at 75rpm for one minute, while its perimeter is held in contact with a test specimen. Corundum is fed between the contact surfaces for the duration of the test. The result of the test is expressed as the chord length of the groove produced in the specimen (see Figure 3-19) adjusted by a calibration factor.

According to the results (see Figure 3-20), RA has only minor effect on the abrasion resistance. The abrasion resistance of RAC for all series is good to very good. In all concrete types, abrasion resistance decreases slightly using RA. C1 series mix with lower strength class shows slightly lower abrasion resistance. Abrasion resistance of recycled aggregate concrete may be expected to increase with the compressive strength of concrete[15].

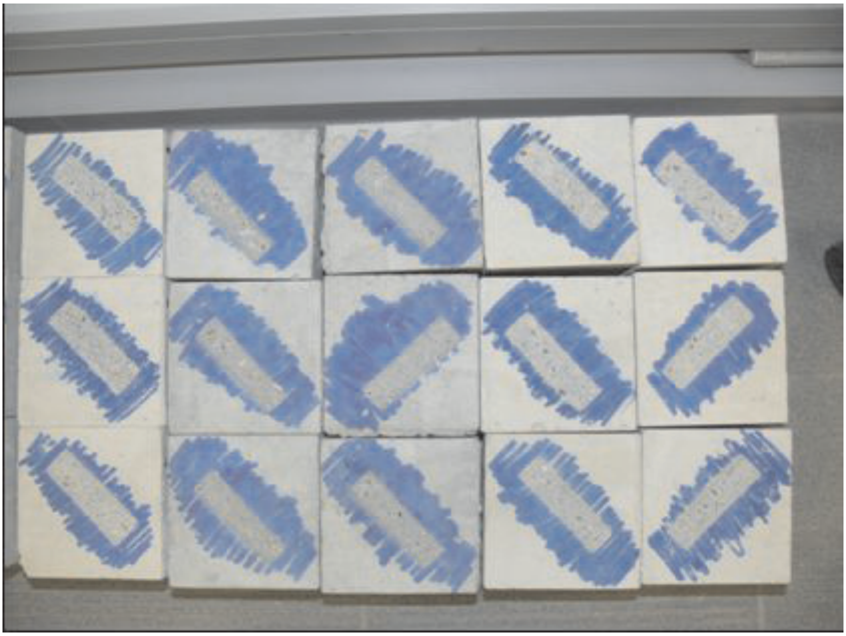


Figure 3-19: Concrete samples after the abrasion resistance test.

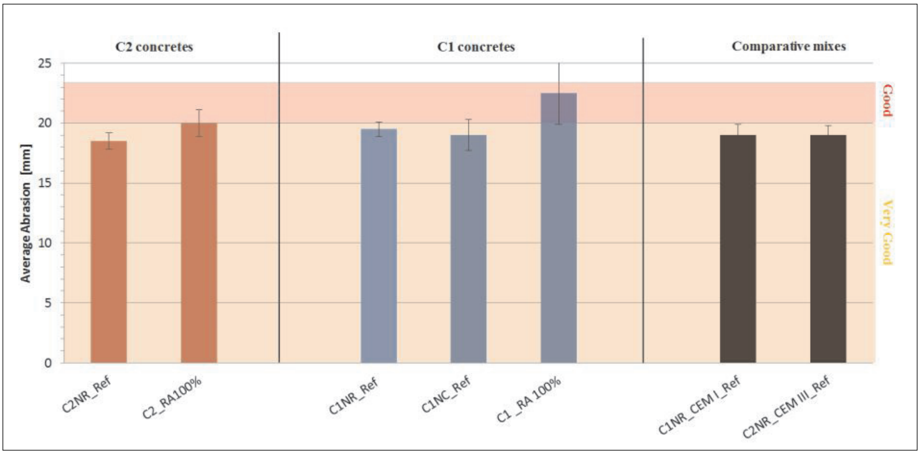
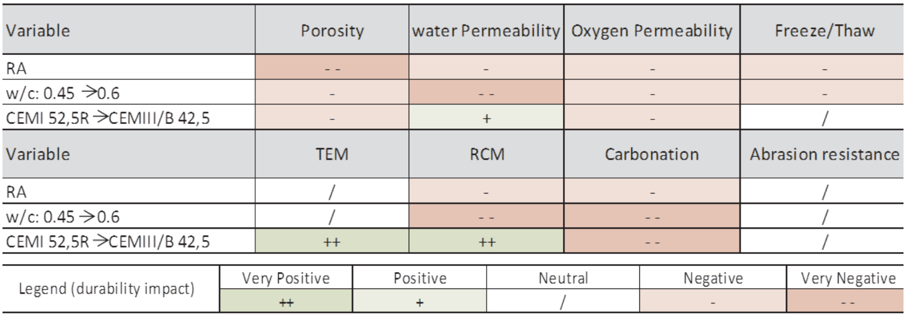


Figure 3-20: Resistance to abrasion. According to EN-1338 values below 20 mm indicate a "very good" resistance and values between 20 and 23 mm a "good" resistance to abrasion.

3.4.4.9 Summary of the durability impact

The overall effect of RA, w/c ratio and type of cement on durability, is summarized in Table 3-9. From the table it is clear that the direct impact of RA substitution, has slightly negative influence. Most of the durability properties in both RAC and NAC can be addressed to a high extent by the choice of cement and w/c in the concrete mixture and detrimental influence of RA even at 100% replacement level is scant.

Table 3-9: Impact of certain variables (RA, w/c, cement) on concrete durability.



Variable	Porosity	water Permeability	Oxygen Permeability	Freeze/Thaw
RA	- -	-	-	-
w/c: 0.45 →0.6	-	- -	-	-
CEMI 52,5R →CEMIII/B 42,5	-	+	-	/
Variable	TEM	RCM	Carbonation	Abrasion resistance
RA	/	-	-	/
w/c: 0.45 →0.6	/	- -	- -	/
CEMI 52,5R →CEMIII/B 42,5	++	++	- -	/

Legend (durability impact)	Very Positive	Positive	Neutral	Negative	Very Negative
	++	+	/	-	- -

3.5 CONCLUSION

In order to reduce the environmental impact of Construction & Demolition Waste, a new concrete recycling process in the context of the European C2CA project has been developed. The aim is in situ mechanical recycling of EOL concrete into high-grade aggregate and low-CO_2 raw material for clinker production. The process applies selective demolition, autogenous milling and ADR as key technologies to deliver cleaner recycled aggregate. Among various liberation routes, autogenous (attrition) milling, offers low complexity (mobile) and low-cost technology to remove the fragile mortar from the surface of aggregates. After milling, ADR efficiently separates the moist material into fine and coarse fraction. In the course of the second demonstration case of this technology (industrial trial), recycled aggregate was tested into new concrete (RAC) to evaluate the influence of RA substitution, w/c ratio and type of cement on the mechanical and durability performance of the RAC. According to the results, using RA as alternative aggregate in concrete might increase the overall porosity of concrete compared to the reference concrete. Besides, applying higher amount of w/c by increasing the effective mixing water induces more porosity to the system that makes the situation more difficult. As it is observed in the experimental results, for example, C1 concrete series with the higher amount of mixing water and lower amount of strength shows in most cases worse mechanical and durability properties than the C2 concrete series. On the other hand, the adverse effect of RA is escalated applying a higher amount of w/c in the system. However, according to C2 concrete results, modifying the concrete mix design, based on lower water to cement ratio and using superplasticizer, results in better mechanical and durability properties in RAC. The mechanical and chemical properties of the cement paste are directly responsible for higher resistance of concrete under exposure to aggressive conditions. Thus, all durability properties can be influenced by the choice of cement and the amount of mixing water in the concrete mixture. Based on the C2CA concrete test program and the current situation in European standards and regulations it is concluded that RA is a suitable alternative to natural coarse aggregates for a significant share of concrete applications including structural applications. Replacing more than 50% if the coarse aggregate with recycled concrete - which corresponds to using more than 500 kg of RA per m^3 of new concrete - needs to be done more carefully and applications should be limited to mild exposure conditions. Regarding the concrete recycling process, more study is recommended to enrich the understanding of the autogenous milling and ADR cut-size impact with respect to the quality of RAC.

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CHAPTER 4

Effects of shear-compression on hardened cement recovery

This chapter is based on the published article:
Lotfi S, Rem P. An experimental study on the recovery of the hardened cement from crushed end of life concrete. EMABM 2015

4.1 ABSTRACT

In the C2CA concrete recycling process, autogenous milling of the crushed End of Life (EOL) concrete is a mechanical method to remove cement paste from the surface of aggregates. During autogenous milling, the combination of shearing and compression forces promotes selective attrition and delivers a better liberation. In order to investigate the effects of shear and compression on the cement recovery and specify the importance of them, a new set-up is designed and constructed. This set-up permits aforesaid forces to be determined and controlled. For experimental design, the MINITAB 16 software was used and 13 different experimental runs based on varying shear and compression forces were conducted. After each experiment, the amount of cement recovery using XRF analysis, water absorption of the recycled aggregates and energy consumption during the process were measured. Results show that both shear and compression forces have influence on improving the cement recovery. With simple changes in the setting of an autogenous mill like bed height or residence time the need for high-cost secondary crushing during concrete recycling could be eliminated.

4.2 INTRODUCTION

One of the main processes considered within C2CA is autogenous milling. After crushing the EOL concrete, liberation of the cement paste is promoted by several minutes of grinding in an autogenous mill[1,2].

The conventional EOL concrete recycling circuit is composed of simple size reduction and classification for RA production. However, it does not deliver a high amount of liberated aggregate and cement paste[3]. According to some studies the liberation of the cement paste in the fine fraction will enhance by increasing the number of crushing processes[4]. A secondary crusher can apply pure compression and bring higher cement recovery. However, using pure compression is not always economic and beneficial. It requires a substantial amount of energy and there is a high possibility of breaking aggregate into the fine fraction.

The idea of using autogenous milling instead of the secondary crushing has a root in a fundamental principle of mineral processing. In mineral processing, one of the aims of comminution is liberation of valuable components separated from gangue. In an autogenous mill, internally created shear and compression forces produce a gentle attrition among particles. Therefore, surface layers, edges or corners from crushed EOL concrete can be removed[5].

In the present study, the influence of shear and compression forces on the cement recovery from EOL concrete was determined. Evidence is presented that the amount of cement recovery in the crushed fine fraction EOL concrete is influenced by both shear and compression forces. The aim of this investigation is to enrich our understanding of the importance of noted forces with respect to the cement recovery and also enable advances in the field of concrete recycling.

4.3 MATERIALS AND METHODS

4.3.1 Parent concrete and primary crushing

Table 4-1 shows the mix design of the parent concrete with the strength class of C30/37. After casting and six months curing of the parent concrete, a jaw crusher with the opening of 20 mm was used for the primary crushing. Figure 4-1 shows the particle size distribution of the crushed parent concrete.

Table 4-1: Mix proportions of the concrete per m^3.

Component	Wet[kg]	Dry[kg]
CEM III/B	330	330
Sand 0,125-0,250 mm	74.72	74.72
Sand 0,250-0,500 mm	242.85	242.85
Sand 0,500-1 mm	242.85	242.85
Sand 1-2 mm	149.45	149.45
Sand 2-4 mm	93.4	93.4
Gravel 4-8 mm	373.61	373.61
Gravel 8-16 mm	691.18	691.18
Water	165	-
Super plasticizer	0.27	-
Total	2363	2198

4.3.2 Set-up for applying shear and compression force

A new experimental set-up with the purpose of applying controlled shear and compression on the bulk crushed concrete was designed and constructed. The schematic of the Shear – Compression Machine (SCM) can be seen in Figure 4-2. The SCM consists of a vertical cylinder for the application the compression force. A ring-shaped container is placed under the vertical cylinder which is connected to an arm. An electrical engine connected to the arm is applied to move the container back and forth with sweep time and displacement of 146 seconds and 0.545 meter respectively. The effective surface area of the container is 0.12 m^2, and for each test it can be filled out with approximately 22 kg of crushed parent concrete.

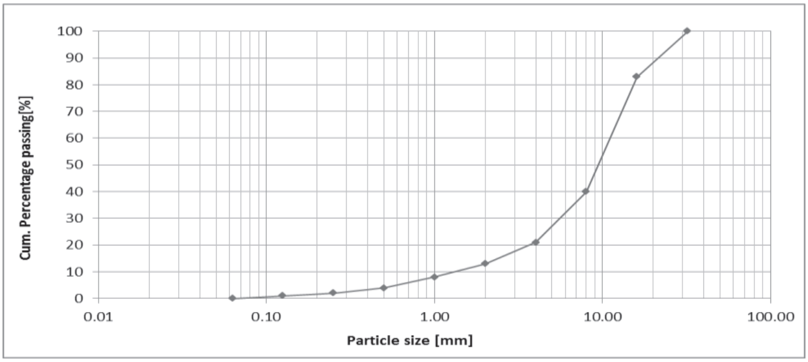

Figure 4-1: Particle size distribution of parent concrete after primary crushing

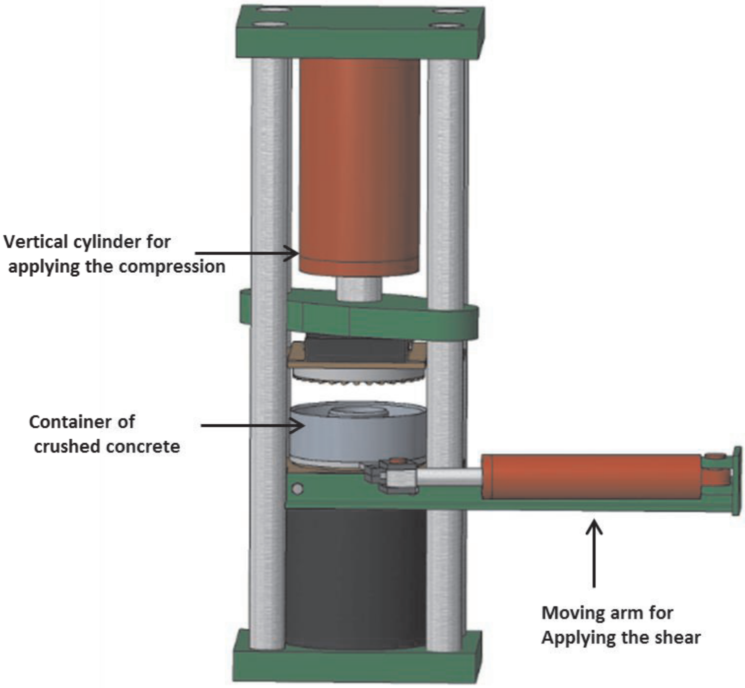

Figure 4-2: Schematic of Shear-Compression Machine(SCM)

4.3.3 Experimental design

In order to figure out the cumulative effects of two variables (shear and compression), it was decided to use Response Surface Methodology (RSM). Within RSM, Central Composite Design (CCD) is a popularly used method[6]. As shown in Figure 4-3, a two-variable CCD is composed of 22=4 factorial points, extended by 2×2 additional axial points and 5 centre points (t_0) (five replications). In general, for a k-variable CCD, the total number of simulated runs T is calculated by:

$$T= 2k + 2k+ t_0$$

Repeating runs at the centre of the design introduces a check on variability and repeatability into the data, providing a means to eliminate noise in the experimental results. The general form of RSM with the second-order model is expressed as:

$$y= \beta_0 + \sum_{i} \beta_i x_i + \sum_{i} \beta_{ii} x_i^2 + \sum_{i\langle j} \beta_{ij} x_i x_j + \varepsilon$$

Where β_i represents the linear effect of x_i, β_{ij} represents the quadratic effect of x_i, β_{ij} represents the interaction between x_i and x_j and ε is the fitting error.

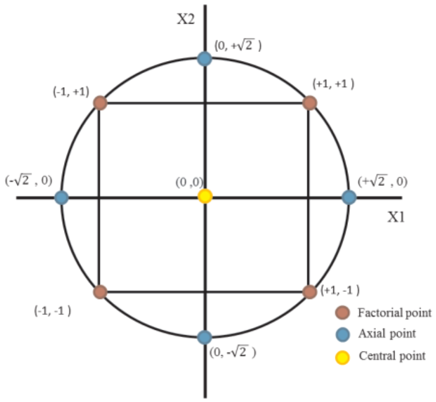

Figure 4-3: Layout of the experiments in a 2-factor Central Composite Design.

In this research, design and analysis of the central composite experiment were carried out using the MINITAB 16 software. The variable of compression was defined as the force exerted by the cylinder, whereas the variable of shear was represented by the duration of the back and forth motion of the arm. Both variables had two different levels (low and high, see Table 4-2). In line with Equation (1), the total number of simulated runs was 13 experiments.

Table 4-2: variables and their level for experimental design.

Variable		Low level	High level
1	Compression: Force(KN)	1.2	36
2	Shear: Duration(min)	2	8

4.3.4 Analysis of the experimental samples

After each experimental run, the particle size distribution of crushed concrete was analysed. XRF analysis for all 0-1mm and 0-0.5mm fractions was conducted and the cement recovery was calculated based on the CaO content. The water absorption of the 4-16 mm fractions was determined to assess the amount of cement paste reduction and the energy consumption for each experimental run was calculated according to the torque measurement on the arm. Figure 4-4 shows the experimental set-up. A sensor was applied to determine the amount of torque and energy consumption during the experiments.

Figure 4-4: Shear-Compression Machine.

4.4 RESULTS AND DISCUSSION

4.4.1 Interpretation of the regression analysis

Experiments were performed according to the experimental plan and the results are given in Table 4-3 along with the results predicted by the model. Table 4-4 and Table 4-5 show estimated regression coefficients for cement recovery in the 0-1 mm and 0-0.5 mm fractions, respectively. Using T-test and P-values regression analysis was carried out. In general, the larger the magnitude of T and the smaller the value of P, the more significant is the coefficient term[6]. Considering Table 4-4 and Table 4-5, the effects of the linear factors on cement recovery are highly significant ($P< 0.001$).

Table 4-3: Full factorial central composite design matrix of two factors, with experimental and predicted response (cement recovery).

Run Order	Force (KN)	Duration (min)	Recovery of cement in (0-1mm)	predicted Recovery of cement in (0-1mm)	Residual	Recovery of cement in (0-0.5 mm)	predicted Recovery of cement in (0-0.5mm)	Residual
1	6.30	2.88	25.00%	23.60%	1,40%	16.89%	15.40%	1,50%
2	18.60	5.00	30.93%	30.90%	0,00%	20.93%	20.10%	0,80%
3	18.60	8.00	35.03%	34.00%	1,00%	23.54%	22.60%	1,00%
4	1.20	5.00	23.31%	24.40%	-1,10%	14.27%	15.40%	-1,10%
5	36.00	5.00	41.66%	40.40%	1,30%	26.38%	25.30%	1,10%
6	18.60	5.00	30.57%	30.90%	-0,40%	19.53%	20.10%	-0,60%
7	6.30	7.12	27.82%	27.70%	0,10%	17.51%	17.40%	0,10%
8	30.90	2.88	33.13%	33.40%	-0,30%	20.19%	20.20%	0,00%
9	18.60	5.00	30.81%	30.90%	-0,10%	20.76%	20.10%	0,70%
10	18.60	2.00	25.38%	26.20%	-0,80%	15.54%	16.50%	-1,00%
11	30.90	7.12	38.77%	40.40%	-1,60%	25.28%	26.70%	-1,40%
12	18.60	5.00	30.90%	30.90%	0,00%	19.47%	20.10%	-0,60%
13	18.60	5.00	31.46%	30.90%	0,50%	19.85%	20.10%	-0,30%

Table 4-4: Estimated regression coefficient for cement recovery into the 0-1 mm fraction.

Term	coefficient	Standard error coefficient	T-Value	P-Value
Constant =(X_0)	0.309341	0.005281	58.577	0.000
Force(KN) = (X_1)	0.079612	0.005904	13.484	0.000
Timing(min) (X_2)	0.039063	0.005904	6.616	0.000
Force(KN)*Force(KN) =(X_1^2)	0.014693	0.008954	1.641	0.145
Timing(min)*Timing(min)=(X_2^2)	-0.008136	0.008954	-0.909	0.394
Force(KN)*Timing(min)=($X_1.X_2$)	0.014098	0.011808	1.194	0.271

S(Standard error)= 0.0118084 R^2 = 97.06% R^2 (adj) = 94.96%

Table 4-5: Estimated regression coefficient for cement recovery into the 0-0.5 mm fraction.

Term	coefficient	Standard error coefficient	T-Value	P-Value
Constant =(X'_0)	0.201083	0.005462	36.816	0.000
Force(KN) = (X'_1)	0.049825	0.006107	8.159	0.000
Timing(min) = (X'_2)	0.030094	0.006107	4.928	0.002
Force(KN)*Force(KN) =(X'^2_1)	0.002352	0.009261	0.254	0.807
Timing(min)*Timing(min)=(X'^2_2)	-0.005516	0.009261	-0.596	0.570
Force(KN)*Timing(min)=($X'_1.X'_2$)	0.022357	0.012213	1.831	0.110

S(Standard error)= 0.0122130 R^2 = 93.12% R^2 (adj) = 88.

A positive sign of a coefficient represents a synergistic effect while a negative sign shows antagonistic effect. In both tables, it can be seen that the linear terms of compression force and shear duration, the quadratic term of force and the interaction term of force and duration have a positive effect on cement recovery. Those coefficients show that with an increase in the amount of force and duration the recovery percentage of cement will increase. Considering the regression coefficients, two regression equations for cement recovery in two different fractions 0-1mm and 0-0.5 mm result as following:

$$Y = 0.309341 + 0.079612\,X_1 + 0.039063\,X_2 + 0.014693\,X_1^2 - 0.008136\,X_2^2 + 0.014098\,X_1.X_2$$

$$Y' = 0.201083 + 0.049825\,X'_1 + 0.030094\,X'_2 + 0.002352\,X'^2_1 - 0.005516\,X'^2_2 + 0.022357\,X'_1.\,X'_2$$

Where Y is the Recovery of cement into the 0-1mm fraction and Y' is the recovery of cement into the 0- 0.5mm fraction. In both tables, the value of S (standard deviation) between the measured and predicted results shows that the equation adequately represents the relation between the response and significant variables. In particular, S is close to the experimental error of the data. The high value of (R^2 = 97.06%, R^2 = 93.12%) and (R^2 (adj) = 94.96%, R^2 (adj) = 88.20%) show high correlation between the observed and predicted values of response.

4.4.2 Interpretation of surface and contour plots

Contour and surface plots give a better understanding of the influence of variables and their interaction on the response. A contour plot provides a two-dimensional view, where all points having the same response are connected to produce contour lines. A surface plot provides a three- dimensional view that may provide a clearer picture of the response surface. Figure 4-5 shows the 3D or 2D plots relationship between two variables (force and timing) and properties like cement recovery, water absorption and energy consumption. According to the results, with increasing the amount of force and duration, the weight of 0-1 mm fraction and the cement recovery are increased. Recovery of cement is affected by both compression and shearing and it is increased to more than 40% in 0-1mm fraction (see Figure 4-5A and B). Decreasing the amount of water absorption in coarse fraction 4-16mm, by increasing the amount of force and timing, is another evidence to prove the reduction of cement paste on the surface of recycled aggregates (see Figure 4-5 C and D). The energy consumption raises by increasing the amount of timing and force . However, according to Figure 4-5 E and F even by using the highest amount of force and timing, the energy consumption is less than 700 kJ/ton (0.19 KWh/ton). It shows that the cost of autogenous milling could stay in a reasonable range during concrete recycling process.

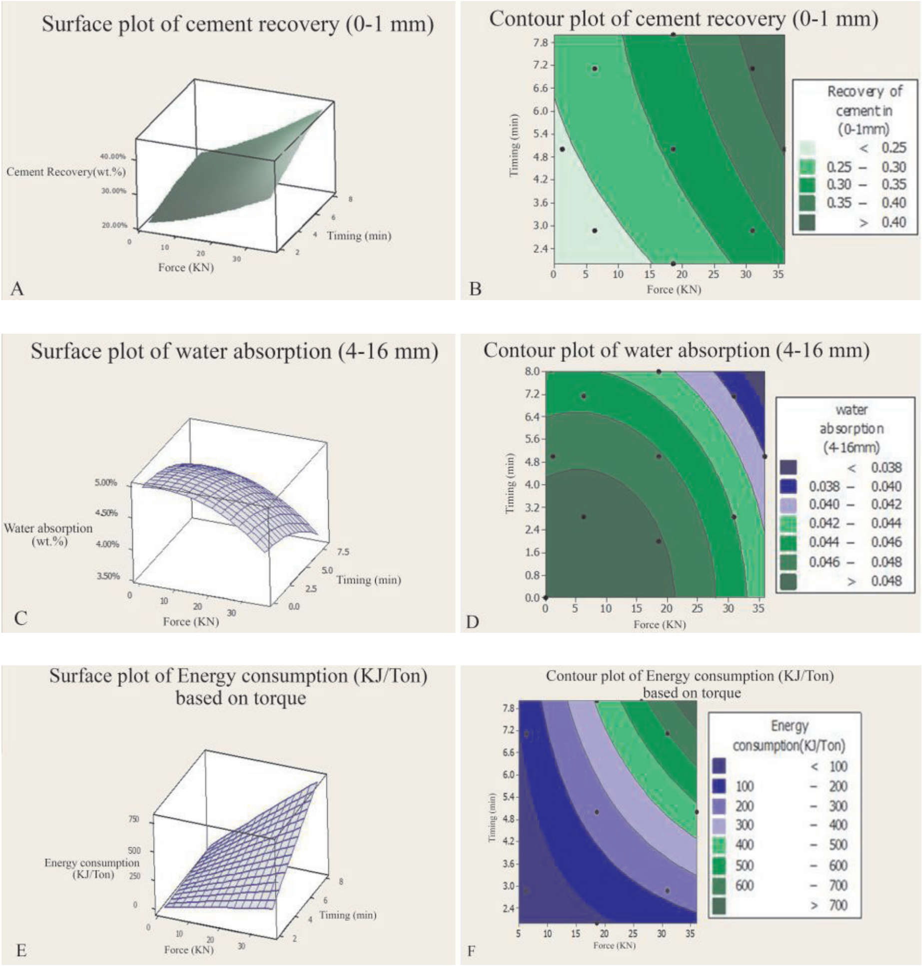

Figure 4-5: A and B- surface and contour plot for cement recovery in 0-1mm, D and E-surface and contour plot of water absorption 4-16mm, E and F-surface and contour plot for energy consumption during milling. In all figures duration of back and forth motion is indicated as timing.

4.4.3 Main effect plot

A main effect is present when different levels of factor influence the response differently. It is created by plotting the response mean for each factor level. A line is drawn to connect the points for each factor and a reference line is also drawn at the overall mean[7]. When the line is not horizontal, there is a main effect present. Different level of the factor affects the response differently. The greater the difference in the vertical position of the plotted points, the greater is the magnitude of the main effect. The main effect of the parameters force and timing on cement recovery from 0-1mm and 0-0.5 mm fraction are given in Figure 4-6 A and B. Reference line in Figure 4-6 A and B is 0.3114 and 0.2001 respectively. From the figures, it is observed that both timing and force have a positive effect on the cement recovery. From the main effect plot, it is obvious that force has slightly more influence.

4.4.4 Normal probability plot

The normality of the data can be checked by plotting the normal probability plot of the residuals. The normal probability plot is a graphical technique for assessing whether or not a data set is approximately normally distributed. Figure 4-7 A and B show normal probability plot of residual values. Trends observed in those figures reveal well-behaved residuals. Based on this plot the residuals appear to be randomly scattered.

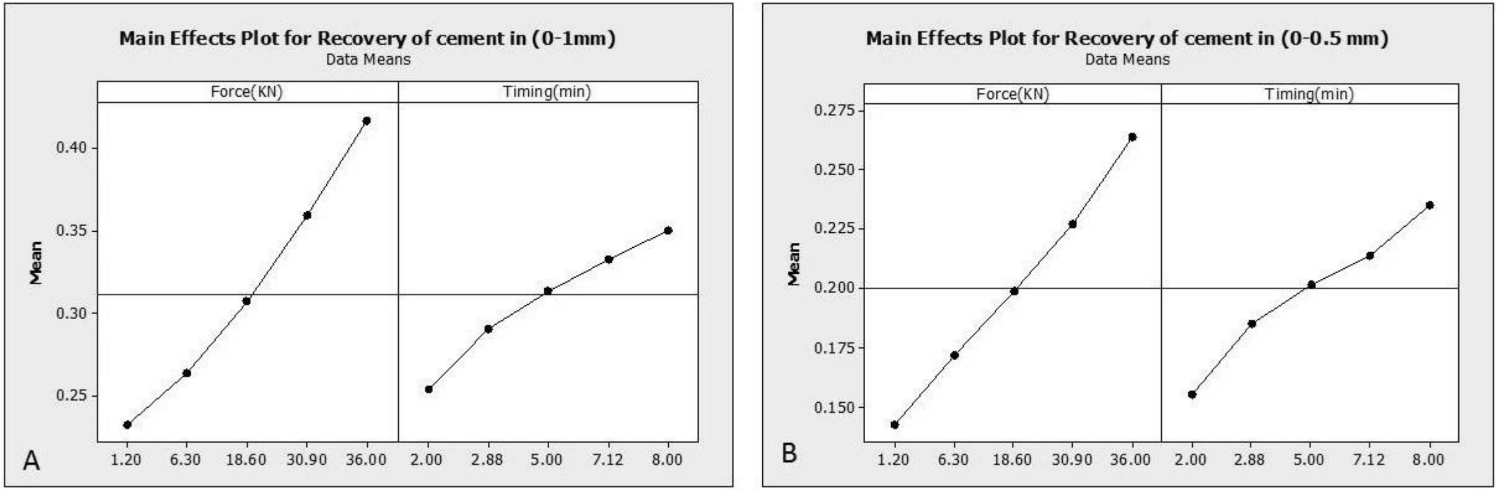

Figure 4-6 A: Main effects plot for recovery of cement in (0-1mm), B: Main effect plot for recovery of cement in (0-0.5mm).

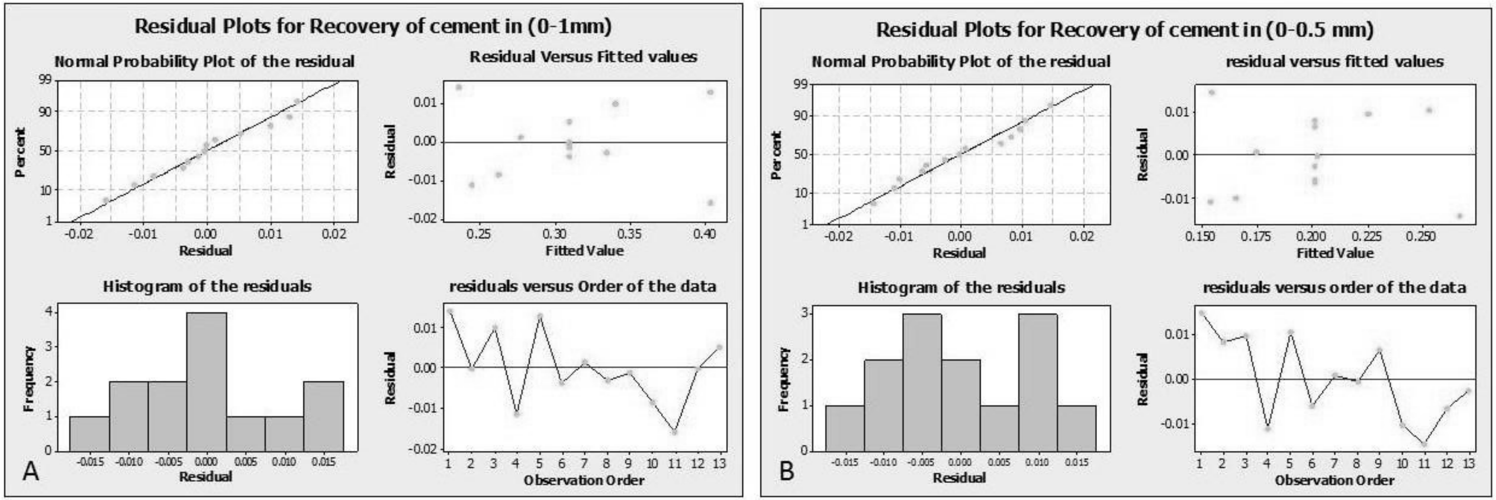

Figure 4-7 A: residual plots of cement recovery in (0-1 mm), B: residual plots of cement recovery in (0-0.5 mm).

4.5 CONCLUSION

In the C2CA concrete recycling process, autogenous milling of crushed end of life concrete is used to increase the liberation of the cement paste. This research is carried out to understand how shear and compression, and the combined effect of them inside of an autogenous mill, influence the cement recovery. In order to simulate forces in an autogenous mill in a controlled way, a new set-up was constructed. A central composite experimental design with the help of the MINITAB 16 software for predicting the results of 13 experimental runs was used. According to the regression analysis, the effect of shear and compression on the cement recovery for both 0-1 mm and 0-0.5 mm fractions was found to be strongly linear ($P< 0.001$). Comparing the main effect plots, force (compression) is slightly more effective than timing (shear). However, based on the achieved results, it is possible to replace the shear and compression with each other with the purpose of raising the cement recovery. Therefore, high amount of produced low-cost shear in an autogenous mill will eliminate the need for the expensive pure compression in a crusher. Variation in the strength of concrete could be compensated by simple changes in the mill feeding, the residence time and the bed height.

4.6 REFERENCES

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CHAPTER 5

The relation between input variables and output quality in the C2CA process

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This chapter is based on the submitted article:

Lotfi S, Deja J, Rem P, Mróz R. A comprehensive study on the relation between input variables and output quality of a new concrete recycling process. Journal of construction and building materials.

5.1 ABSTRACT

The C2CA process consists of a combination of smart demolition, gentle grinding of the crushed concrete in an autogenous mill, and a novel dry classification technology called ADR to remove the fines. The main factors in the C2CA process which may influence the properties of Recycled Aggregates (RA) or Recycled Aggregate Concrete (RAC) include the type of Parent Concrete (PC), the intensity of autogenous milling (changing the amount of shear and compression inside of a mill) and the ADR cut-size point (usage of +2mm or +4mm RA in the new concrete). This study aims to investigate the influence of implied factors on the quality of the RA and RAC. To conduct the study, first of all, three types of concrete which are mostly demanded in the Dutch market were cast as PC and their fresh and hardened properties were tested. After near one year curing, PC samples were recycled independently varying the type of PC and intensity of the autogenous milling. Experimental variables resulted in the production of eight types of RA. The physical, mechanical and durability properties of the produced RA were tested and the effect of the experimental variables on their properties were investigated. According to the results, the type of PC is a prevailing parameter for the final properties of RA, in comparison with the milling intensity. Moreover, it is observed that a variation in the milling intensity mostly influences the properties of RA produced from a lower strength PC. Experiments were followed by studying the performance of the RA in the new concrete. Four types of RAC were produced based on the modified recipe of their corresponding PCs. For the modification of the recipes, water absorption and density of RA were taken into account while the amount of applied cement and consistency class was kept similar to the corresponding PC. Experimental results show that the compressive strengths of all produced RAC samples were higher than PC, especially at early ages. The increasing rate of compressive strength for different types of RAC was found to be mostly influenced by the type of PC and the autogenous milling intensity. Among various autogenous milling intensities, milling at medium shear and compression delivers better properties for RA and RAC. Good performance of RAC with the incorporation of 2-4mm ADR fines and RA, confirms the possibility of setting ADR cut-size point on 2 mm.

5.2 INTRODUCTION

In the coming years, a strong increase of the amount of CDW is expected in Europe because of the large number of construction from the 1950s which are closing to their end of life[1]. End of life concrete is known to be the heaviest component of the CDW. Considering the fact that public and private sectors have become aware of the urgency and importance of CDW recycling, the European Commission has taken initiatives towards sustainable treatment and recycling of CDW. In this regards, a novel concrete to concrete recycling process (C2CA) is developed within a European project with the full title of "Advanced technologies for the production of cement and clean aggregates from construction and demolition waste". C2CA process aims at a sustainable and cost-effective system approach for recycling of high-volume EOL concrete streams into prime-grade aggregates and cement[2].

The technologies considered are smart demolition to produce crushed concrete with low levels of contaminants, followed by mechanical upgrading of the material on-site into an aggregate product with sensor-based on-line quality assurance and a cement-paste concentrate that can be processed into a low-CO_2 input material for new cement. In C2CA process, after crushing and sorting out big contaminants, liberation of the cement paste is promoted by several minutes of grinding in an autogenous mill while producing as little as possible new fine silica. A new low-cost classification technology, called Advanced Dry Recovery (ADR) is then applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles[3].The feasibility of this recycling process was examined in a demonstration project involving 20,000 tons of EOL concrete from two office towers in Groningen, the Netherlands and delivered very promising results[1].

Fine tuning of the C2CA process, requires a comprehensive understanding of the effects of various influencing parameters. In C2CA process, the main factors which could affect the final properties of RA and RAC include the type of PC, the setting of ADR cut-size and the intensity of autogenous milling.

In spite of the availability of considerable research aimed at a better understanding of the properties of RA and their influence on the performance of RAC, there are limited studies focusing on the effects of the involved recycling parameters in relation with the quality of final products[5-8]. Some research indicate the effect of parent concrete on the properties of the recycled aggregate concrete. According to Akbarnezhad et al. the PC properties such as strength and size of Natural Aggregates (NA) can strongly affect the properties of RA[8]. Kou et al. reported that RA derived from PC with high strength (80 to 100 Mpa) can be used to replace 100% with NA[7]. However, other researchers claimed that for the same particle size, aggregates coming from weaker PC have greater dry density and less attached mortar which would result in a better quality concrete[8]. Similar to that, Padmini et al. reported that RA produced from PC with higher strength have higher amount of water absorption[5]. They also reported that for a given target strength, with increasing the strength of parent concrete, the strength of RAC reduces. However, Tavakoli et al. reported that if the compressive strength of the original concrete is higher than that of the control concrete, then the recycled aggregate concrete can also be made to have higher compressive strength than the control concrete[6]. They also expressed that increasing in water absorption capacity of RA, which partly reflects the increased amount of mortar adhered to original stone, lead to reduced compressive strength of RAC.

In addition to above mentioned research, there have been also few efforts to increase the quality of RAC through the production processes[2,6,8,9]. It is reported that the liberation of cement from surface of aggregates will improve using an autogenous mill[9,10]. However, the effect of autogenous milling intensity and its importance for recycling of different types of concrete is not yet well understood.

On the other hand, the effect of ADR cut-size on the performance RAC needs to be investigated. ADR is equipped with an adjustable cut-size point by which the separation of aggregates can be done on 2 mm or 4 mm. Setting ADR cut-size on 2 mm means that recycled fines will be partially incorporated for RAC production. Considering the fact that fines are massive by product of the concrete recycling process, it would be beneficial to use them partially in the RAC production. Evagelista et al. did a comprehensive review on existing reports related to the utilization of recycled fines in new concrete[11]. From their review they concluded that although the use of fines in concrete production is currently considered unacceptable by a major part of scientific community, some published results prove that if the problem is approached correctly, it is possible to make concrete containing recycled fines that affords high performance. However, due to existing diverse results, it deserves more investigation.

The aim of current study is to enrich the knowledge with respect to the fine setting of C2CA process to deliver RA and RAC with high quality and salability potential. The present paper reports on the findings of an experimental study on the influence of the above explained parameters "the type of PC, milling intensity and ADR cut-size point" on the performance of RA or RAC.

5.3 MATERIALS AND METHODS

5.3.1 Parent Concrete

Three series of mostly utilized concrete in the Dutch market were chosen for casting as the Parent Concretes (PCs). To produce the specimens, ready mix concrete with real applications (see Table 5-1) and provided by Mebin (Heidelbegcement in the Netherlands), were used. The mix proportions for considered types of PC are presented in Table 5-2. PCs consists of CEM III B 42,5 NLH and aggregates at three different grading with maximum sizes of 16 mm (for PC3) and 31,5 mm (for PC1 and PC2) (see Figure 5-1). PC1 and PC3 contain just NA, while PC2 consists of 10 wt.% of 16-32 mm RA in addition to NA due to the actual industrial usage of RA in the Netherlands. All specimens were cast in molds and compacted using vibrators (see Figure 5-2). Samples were demolded after 24 h in a controlled laboratory environment and were cured in the standard condition according to the EN-12390-2. Fresh and hardened properties of the parent concretes were determined (see Table 5-3) and the rest of the specimens were remained into the curing room for a duration of one year. For each type of PC about 100 cubes of concrete (15cm×15cm×15cm) were casted.

Table 5-1: Applications of the utilized parent concrete (PC) according to the descriptions in the EN 206-1.

Parent concrete code	Concrete Class	Place of utilization	Consistency Class	Environmental class
PC1	C28/35 D32	Wall	S3	XA2
PC2	C20/25 D32	Floor	S3	XC1
PC3	C20/25 D16	Wall	S3	XC3

Table 5-2: Mix proportions of Parent Concretes (PCs).

Component	PC1		PC2		PC3	
	Mass(kg)	Volume (dm^3)	Mass(kg)	Volume (dm^3)	Mass(kg)	Volume (dm3)
CEM III B 42.5 N LH	337	115	260	89	324	111
water	173	173	180	180	187	187
NA 4-32 mm	1006	383	833	315	-	-
NA 4-16 mm	-	-	-	-	998	378
RA 4-32mm	-	-	200	79	-	-
NS 0-4mm	823	314	835	316	792	301
NS 0-1mm	-	-	16	6	23	9
Total weight of aggregates and sand (kg)	1829		1884		1813	
Air content(dm3)	15		15		15	
w/c ratio	0.51		0.69		0.58	

*NA: Natural Aggregate, RA: Recycled Aggregate, NS: Natural Sand

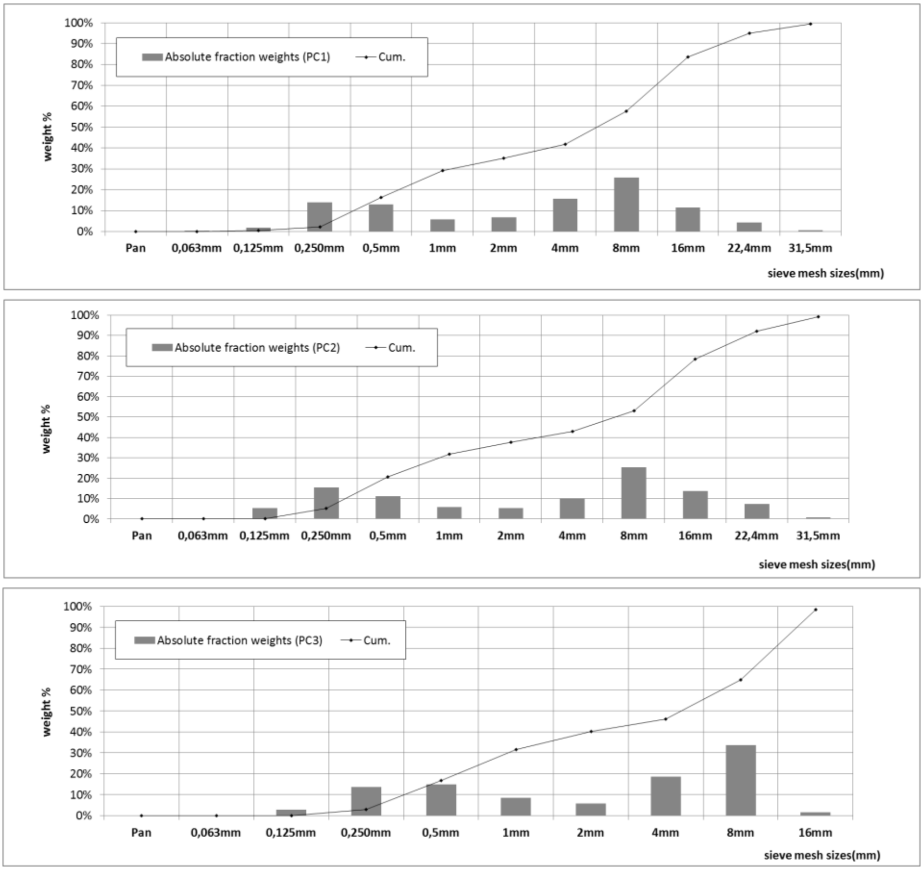

Figure 5-1: Grading of the aggregates and sand used in parent concrete as well as concrete made with RA.

Figure 5-2: Sampling and casting of the parent concretes.

Table 5-3: Fresh and hardened properties of the Parent Concretes (PCs).

Properties	Standard	PC1		PC2		PC3	
		Measured results	SD	Measured results	SD	Measured results	SD
Fresh Properties							
Slump(mm)	EN 12350-2	136	n/a	117	n/a	137	n/a
Slump flow (mm)	EN 12350-5	467	n/a	500	n/a	470	n/a
Hardened Properties (Mpa)							
7-Days compressive strength	EN 12390-3	24.7	1.2	14.6	0.2	20.1	0.4
28-Days compressive strength	EN 12390-3	45.7	1.3	31.1	0.8	37.5	1.7
91-Days compressive strength	EN 12390-3	53.8	4.1	42.0	2.43	47.7	0.1
Durability Properties							
RCM (Rapid Chloride Migration) (10-12m^2/s)	NT BUILD 492	3.93	1.68	14.37	0.85	5.00	2.36
TEM (Ωm)	CUR C177	180.33	n/a	80.33	1.53	168.00	0.78
Carbonation depth (90 days) (mm)	CEN/TS 12390-10	2.95	0.35	3.80	0.28	3.05	0.78
Freeze-thaw resistance total scaled material after 56 cycles (kg/m^2)	CEN/TS 12390-9	2.98	n/a	9.64	n/a	3.62	n/a

5.3.2 Concrete Recycling Procedure

After almost one year curing, PCs were used as the input of the recycling process. Based on an experimental plan different types PC samples were recycled separately. For recycling, a lab-scale version of C2CA process was applied. Firstly, a laboratory jaw crusher with the opening of 20 mm was used to crush the parent concrete samples.

In an industrial site, after crushing, EOL concrete is grinded in an autogenous mill to remove the fragile mortar from the surface of aggregates. During autogenous milling, the combination of shearing and compression forces, promotes selective attrition and delivers a better liberation. Thus, the milling intensity depends on the mentioned shear and compression forces. In this study, for grinding the crushed concrete and studying the influence of the milling intensity in a controlled way, a new experimental set-up was designed and constructed[9]. The schematic of this set-up with the name of Shear-Compression Machine (SCM) can be seen in Figure 5-3. The SCM consists of a vertical cylinder for the application of the compression force. A ring-shaped container is placed under the vertical cylinder which is connected to an arm. An electrical engine connected to the arm is applied to move the container back and forth. The effective surface area of the container is 0.12 m^2, and for each test it can be filled out with approximately 22 kg of crushed PC.

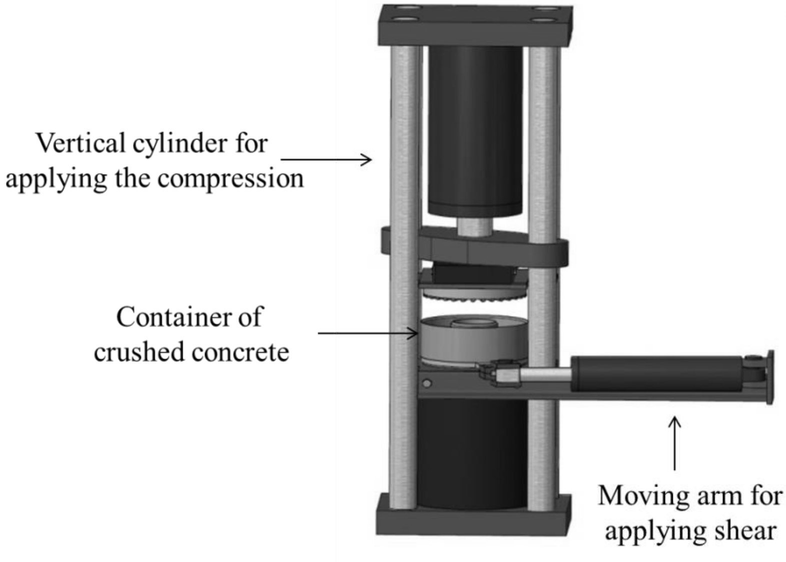

Figure 5-3: The schematic of the Shear-Compression Machine (SCM).

In this study, milling of materials in SCM was followed by a 16 mm screen and an ADR with the capacity of 60 tons per hour. Basically ADR is used to break the bonds that are formed by moisture and fine particles to separate them from coarse particles. The working principle of ADR is schematically shown in Figure 5-4.

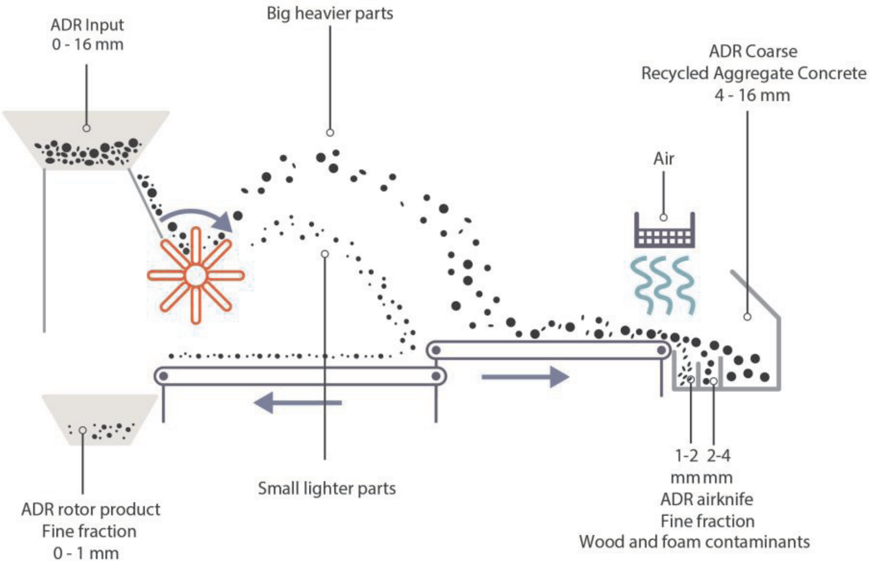

Figure 5-4: Schematic of the ADR principle.

In an industrial recycling site, ADR input materials usually contain certain amount of moisture. To simulate the same condition in the laboratory, the ADR input materials were moisturized artificially (water was added with the amounts of 5wt% of ADR input materials). In ADR after breaking up the material into a jet, the fine particles are separated from the coarse. ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product. Moreover, a fine fraction including the cement paste and contaminants such as wood, plastics and foams (in real conditions where EOL concrete contains pollutants) is separated in another stream. Figure 5-5 shows different steps of the recycling process performed in this study.

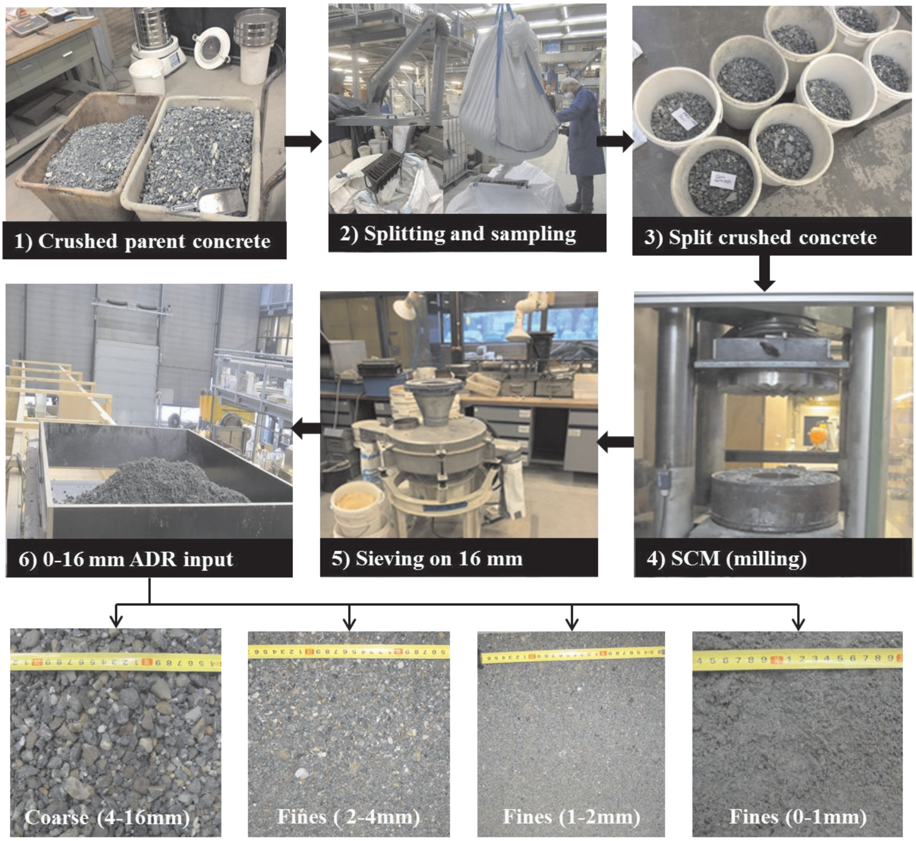

Figure 5-5: Different steps of the performed recycling process and final produced recycled fractions.

5.3.3 Experimental Design

Experiments were designed to investigate the effects of the milling intensity, PCs types on the properties of the RA. The experimental series lead to the production of eight different types of RA (4-16 mm ADR coarse product). Layout of the experiments can be seen in Figure 5-6. Four types of RA were chosen for RAC production. In addition, one type of RAC with incorporation of +2 mm ADR output was produced to study the effect of the ADR cut-size (RAC5). Table 5-4 gives more detailed information about the considered experimental factors, their variables, coding of the produced RA and their corresponding RAC.

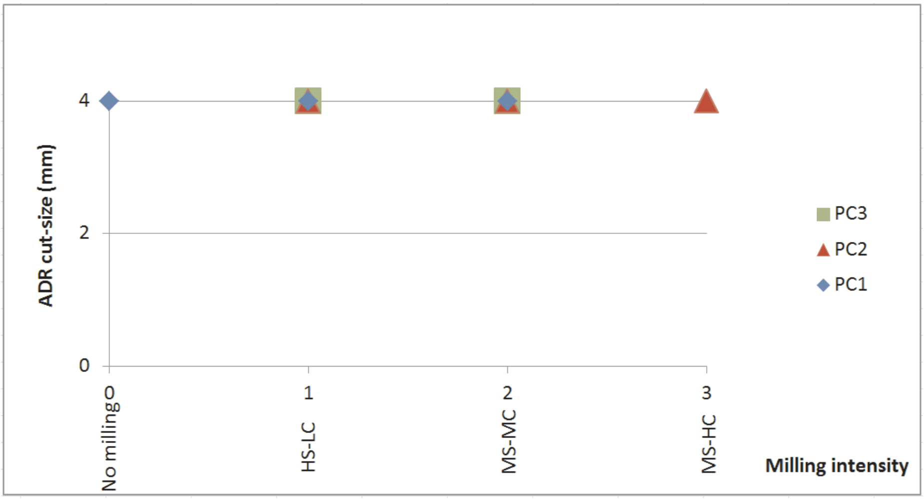

Figure 5-6: Experimental variables to produce eight different series of RA.

Table 5-4: Coding of the produced RA and their corresponding RAC.

Parent concrete	SCM setting (degree of milling)			Coding of ADR input samples	Coding of corresponding produced RA	Corre-sponding produced RAC
	Shear: Duration (min)	Compression: Force (KN)	Coding			
PC1	-	-	no milling	PC1-No Milling	◆ RA-PC1-No Milling	-
PC1	7.12	6.30	HS-LC	PC1-HS-LC	◆ RA-PC1-HS-LC	-
PC1	5.00	18.60	MS-MC	PC1-MS-MC	◆ RA-PC1-MS-MC	RAC1
PC2	7.12	6.30	HS-LC	PC2-HS-LC	▲ RA-PC2-HS-LC	-
PC2	5.00	18.60	MS-MC	PC2-MS-MC	▲ RA-PC2-MS-MC	RAC2
PC2	5.00	30.90	MS-HC	PC2-MS-HC	▲ RA-PC2-MS-HC	-
PC3	7.12	6.30	HS-LC	PC3-HS-LC	■ RA-PC3-HS-LC	RAC3 and RAC5
PC3	5.00	18.60	MS-MC	PC3-MS-MC	■ RA-PC3-MS-MC	RAC4

*S=Shear, *C= Compression, H*=High, *L=Low, *M=Medium

Table 5-5 shows the list of tests and corresponding standards for determining the properties of RA, also fresh and hardened properties of concretes.

Table 5-5:Test methods used for determining properties of RA and hardened RAC.

Test	Standard
RA	
Density SSD[kg/m3]	EN 1097-6
Water Absorption[wt.%]	EN 1097-6
Resistance to crushing[wt. %]	PN-B-06714-40
Resistance to Freezing and Thawing[wt. %]	EN 1367-1
RAC	
Compressive strength	EN 12390-3
Accelerated carbonation	CEN/TS 12390-10
Freeze/thaw resistance	CEN/TS 12390-9

5.3.4 RAC production

ADR coarse products were selected for testing in new concrete applying the recipe of their corresponding PC (see selected ones in Table 5-4). RA tends to absorb more water in comparison with NA due to the residue mortar adhered to the original aggregates. Many research attempt to address this issue by increasing the water and cement content in order to achieve the required workability at a constant water to cement (w/c) ratio. However, higher cement content can affect the properties of hardened concrete like shrinkage besides being not sustainable nor economical. Considering these issues, in one of the previous concrete trials of C2CA, samples of RAC and Natural Aggregate Concrete (NAC) were made separately with the same amount of cement and consistence[2]. After testing the samples, RAC showed almost 30% higher compressive strength after 7 days and the results of the freeze-thaw resistance of RAC fulfilled the F100 class requirement from PN-B 06250 Polish standard. This requirement is applied for usage of concrete in severe environmental conditions. Following the mentioned study, in this research samples of RAC were made with the same amount of cement and consistency class similar to their corresponding PC. Utilized NA, Natural Sand (NS) and cement in both PC and RAC were always from the same source. Based on initial recipes of PC, fresh concrete mixes were prepared with a laboratory mixer (18 dm^3), and afterward the properties of the fresh PC mixes were used as basic information for modification of RAC recipes. The modified concrete recipes for RAC can be seen in Table 5-6 which is comparable to the PC recipes in Table 5-2. RAC5 is the only concrete mixture which contains both ADR coarse RA and ADR 2-4 mm fine fraction. RA substitution percentage in all series of RAC was 100% replacement of the 4-16 mm fractions in parent concretes. Superplasticizer (polynaphthalene sulfonate based liquid admixture) was dosed to all RAC series to achieve the targeted consistency of S3 (125 +/- 25 mm slump). After mixing procedure and filling the molds, samples were cured according to EN 12390-2.

Table 5-6: Composition of RAC mixtures in five different series.

Component	RAC1		RAC2		RAC3		RAC4		RAC5	
	Mass (kg)	Volume (dm^3)	Mass (kg)	Volume (dm^3)	Mass (kg)	Volume (dm^3)	Mass (kg)	Volume (dm^3)	Mass (kg)	Volume (dm^3)
CEM III B 42.5 N LH	340	116	266	91	328	112	329	112	325	111
water	164	164	161	161	176	176	172	172	182	182
NA >31.5mm	11	4	-	-	-	-	-	-	-	-
NA 22.4-31.5mm	81	31	85	32	-	-	-	-	-	-
NA 16-22.4mm	213	81	212	80	29	11	30	11	29	11
NA 4-16mm	-	-	-	-	-	-	-	-	-	-
RA-PC1-MS-MC-ADR 4-16mm	658	293	-	-	-	-	-	-	-	-
RA-PC2-MS-MC->31.5 mm	-	-	12	5	-	-	-	-	-	-
RA-PC2-MS-MC-22.4-31.5 mm	-	-	49	21	-	-	-	-	-	-
RA-PC2-MS-MC-16-22.4mm	-	-	45	20	-	-	-	-	-	-
RA-PC2-MS-MC-ADR 4-16mm	-	-	593	259	-	-	-	-	-	-
RA-PC3-HS-LC-ADR 4-16mm	-	-	-	-	846	363	-	-	841	361
RA-PC3-MS-MC-ADR 4-16mm	-	-	-	-	-	-	863	365		
RS-PC3-HS-LC-ADR 2-4 mm	-	-	-	-	-	-			93	40
NS 0-4mm	775	295	825	314	842	320	847	322		
NS 0-2 mm	-	-	-	-	-	-	-	-	732	278
Aggregates and sand total	1738	-	1821	-	1717	-	1740	-	1695	
Percentage of RA and RS in concrete composition	37.9%	-	38.4%	-	49.3%	-	49.6%	-	55.1%	-
Superplasticizer (kg)	2	2	2	2	2	2	2	2	2	2
Air content (dm^3)	-	15	-	15	-	15	-	15	-	15
w/c ratio	0.48		0.61		0.54		0.52		0.56	

*NA: Natural Aggregate, RA: Recycled Aggregate, NS: Natural Sand, RS: Recycled Sand

5.4 RESULTS AND DISCUSSION

5.4.1 ADR Performance

For each experimental run particle size distributions of ADR input and outputs were determined. Results of the particle size distribution analysis of different ADR coarse products showed negligible variations. Particle size distributions of ADR input and outputs and the recovery of each size fraction of all ADR products for sample PC3-MS-MC (as an example) are shown in Figure 5-7 and Figure 5-8 respectively.

5.4.2 Properties of RA

Table 5-7 shows the physical and mechanical properties of produced RA. The guideline prepared by RILEM recommends recycled coarse aggregates for concrete production if their water absorption is between 3% and 10%[12]. According to recommendations of an international committee, coarse RA having water absorption capacity more than 7% is not desirable to be used in concrete [13]. In general, the values obtained for water absorption of RAs in this study corresponds well with the recommendations. It is well-known that the properties of RA vary proportionally with the amount of mortar present in RA. Research shows that when the mortar content of RA increases, the density of RA drops and the water absorption rises [14].

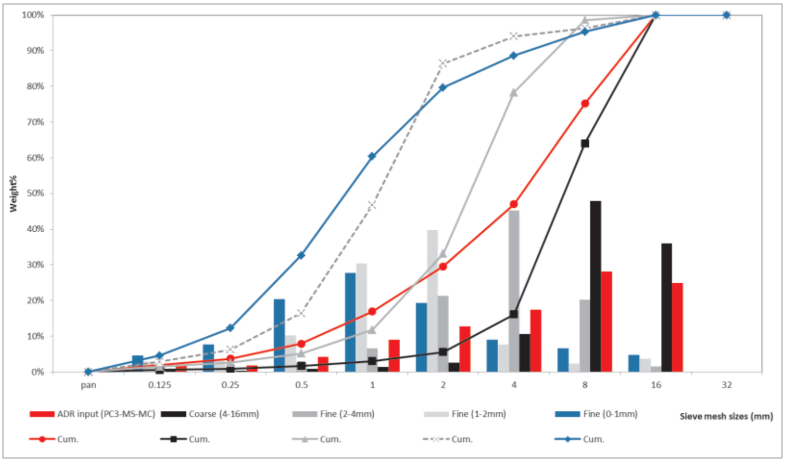

Figure 5-7: Particle size distribution of ADR input and outputs. The lines show the cumulative curves whereas the bars indicate the absolute fraction weights.

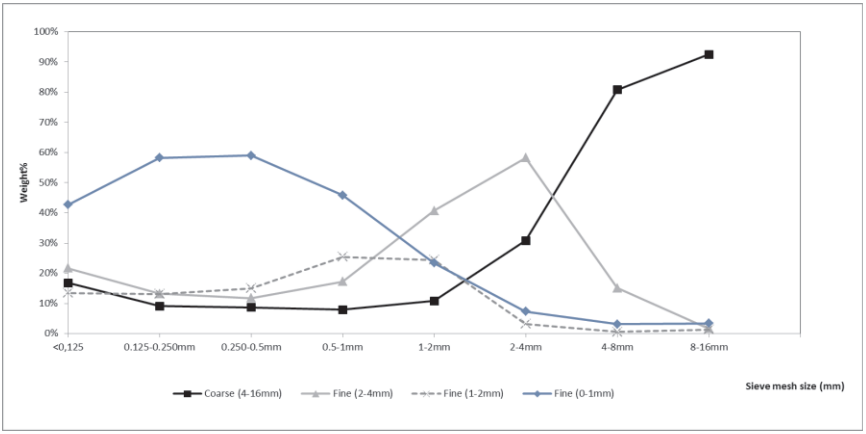

Figure 5-8: The recovery percentage of each size fraction into the three products of ADR for sample PC3-MS-MC.

In the present study, to investigate the importance level of two contributing parameters (milling intensity and type of PC) during recycling and their effects on the overall quality of RA, the variation in the water absorption of RA was utilised.

Figure 5-9 shows the effect of PC type and milling intensity on the water absorption of RA. In the figure type of PC is indicated with its 28 days achieved compressive strength. According to this figure the water absorption of RA generally decreases with reduction in parent concrete strength (Compare PC1 and PC2 which have the same maximum grain size but different strength). This trend is more obvious for RA coming from milling with higher intensity (MS-MC). This may be attributed to the fact that the stronger mortar present in the RA produced from parent concrete with higher strength, results in less mortar being removed during the primary crushing or by increasing the intensity of milling. Considering three different milling intensity (HS-LC, MS-MC and no milling) applied for PC1 which is the strongest utilised PC, it is obvious that changing the milling intensity has a slight effect on the water absorption of RA coming from PC1. On the other hand, water absorption of RA coming from weaker concretes is more influenced by changing the milling intensity.

Comparison between Figure 5-9 and Figure 5-10 shows an inverse relation between the water absorption and density of RA. In Figure 5-10 it is clear that RA coming from PC1 with higher compressive strength, has lower density and density varies slightly by changing the milling intensity. This is another confirmation to the fact that milling intensity changes the mortar content for concretes with weaker strength more effectively. Results also showed that crushing of the PC to a maximum size close to that of their NA may result in some improvement in the density of RA (see PC3 with maximum NA grain size of 16 mm close to 20mm opening size of the crusher). The smaller difference between the size of the NA in PC and the space between the jaws of the crusher leads to the production of less amount of RA which contains more than one grain of NA adhered together and surrounding by mortar[8].

Crushing index is a parameter used to measure resistance of aggregate to fragmentation. Crushing index of various samples in Table 5-7 is another prove for existing a stronger mortar attached to RA coming from a stronger PC. Because of the adhered mortar, sometimes RA could result in higher crushing index. For good quality coarse aggregates according to the requirements of PN-B-06714-40, the crushing index should be less than 16% which corresponds well with the results of this study (see Table 5-7). According to this table, the crushing index of RA coming from PC1 is just slightly higher than that coming from PC2 and PC3. Taking into account that RA coming from PC1 have relatively higher water absorption, one would expect also higher amount of crushing index due to the existence of more attached mortar. Thus, it can be concluded that the mortar attached to RA coming from PC1, is very strong and cannot be removed easily even after the crushing resistance test.

Considering Table 5-7 the influence of the type of PC can be observed also on the durability of RA. A comparison between compressive strength of PC and freeze-thaw resistance of RA, showed in general an inverse relationship (see Figure 5-11- red data points). On the other hand, according to Figure 5-11, the correlation between freeze-thaw resistance of RA and freeze-thaw resistance of PC indicates a strong influence of the type of PC on the freeze-thaw resistivity of RA (see blue data points in Figure 5-11). In general, the results of the experiments on the produced recycled aggregates, indicate the qualification of all types of studied RA for RAC production. According to the Polish national standard for the crushing resistance, all types of RA are ranked as “good”. Durability differences are clearly visible for RA obtained from different PC. RA with the source of PC1 and PC3 presented really good freeze-thaw resistance (category F1 and F2 respectively) in contrast to RA coming from PC2 which showed weaker durability properties (Category F4). The relationship between the RA properties and considered recycling parameters, strongly suggests that the type of the PC is a prevailing parameter for the final properties of RA, in comparison with the milling intensity.

Table 5-7: Physical and mechanical properties of recycled aggregates.

Properties	RA-PC1-No milling	RA-PC1-HS-LC	RA-PC1-MS-MC	RA-PC2-HS- LC	RA-PC2-MS-MC	RA-PC2-MS-HC	RA-PC3-HS-LC	RA-PC3-MS- MC
Moisture content[wt.%]	5.7	5.8	5.8	5.6	5.5	5.7	4.6	4.1
Density of grains[kg/m^3]	2626	2628	2629	2626	2629	2611	2626	2625
Density of grains dried in an oven[kg/m^3]	2265	2256	2249	2266	2290	2262	2330	2358
Density of grains saturated and surface-dried [kg/m^3]	2402	2397	2393	2403	2419	2395	2442	2460
Water absorption[wt.%]	6.06	6.26	6.41	6.04	5.62	5.89	4.82	4.30
Freezing-thawing weight loss (8-16mm) [wt.%]	1.06	0.75	0.91	2.14	3.53	2.32	1.3	1.22
Freezing-thawing weight loss (4-8mm) [wt.%]	1.86	1.69	1.96	5.40	6.01	7.43	2.54	2.35
Index of aggregate crushing for non-fractioned sample [wt.%]	14.42	14.6	14.43	13.74	13.79	13.16	13.21	13.98
Index of aggregate crushing for 4-8 mm fraction[wt.%]	13.49	13.84	13.38	14.02	13.32	13.31	12.74	13.04
Index of aggregate crushing for 8-16 mm fraction[wt.%]	15.65	15.88	15.86	13.31	14.37	12.95	13.93	13.65
Fines content[wt.%] (wet analysis)	0.63	0.23	0.37	0.29	0.31	0.43	0.40	0.34

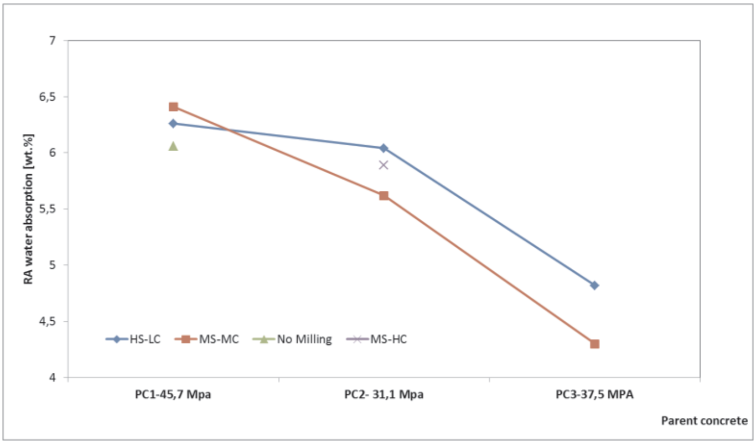

Figure 5-9: The effect of the PC type and milling intensity on the water absorption of RA.

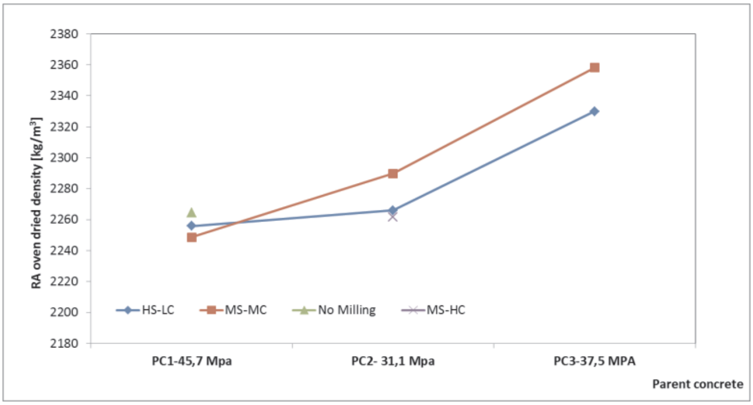

Figure 5-10: The effect of the PC type and milling intensity on oven dried density of RA.

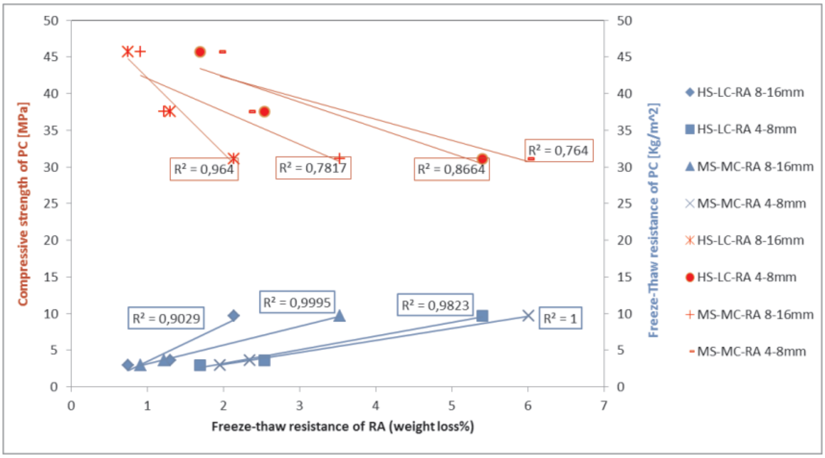

Figure 5-11: Correlation between freeze-thaw resistance of RA and compressive strength of PC and correlation between freeze-thaw resistance of RA and freeze-thaw resistance of PC.

5.5 PERFORMANCE OF RAC

5.5.1 Fresh and hardened concrete mechanical properties

Fresh concrete properties for RAC and PC can be compared in Table 5-8. Considering this table, it is clear that the same consistency class (S3) was achieved for all concrete mixtures. In comparison with the previous study of C2CA[2], in this study slightly lower w/c ratio was achieved during RAC production compared to their original PC. Changing the type of cement (CEM III instead of CEM I that was used in the previous study) also using a more modified admixture in this study could be the cause of this difference. Changing the milling intensity and ADR cut-size alters the amount of w/c ratio slightly (Compare RAC3 with RAC4 for the milling intensity and RAC3 with RAC5 for ADR cut-size point).

Figure 5-12 shows the compressive strength of different RAC, with the standard deviations resulting from the tests done in triple. Considering the figure, it is clear that RAC samples achieved higher compressive strength especially at early ages in comparison with their corresponding PC.

Table 5-8: Fresh properties of RACs and PCs.

Fresh properties of concretes		Water/Cement ratio -Workability-Consistency						
		RAC				PC		
Concrete code	Code of utilized RA	Water absorption of RA (4-16mm)	W/C	Slump [mm]	Slump class according to EN 206-1	W/C-Correspondent PC	Slump [mm]-Correspondent PC	Slump class according to EN 206-1
RAC1	RA-PC1- MS-MC	6.41	0.48	130	S3	0.51 - PC1	136 - PC1	S3
RAC2	RA-PC2-MS-MC	5.62	0.61	125	S3	0.69 - PC2	117 - PC2	S3
RAC3	RA-PC3-HS-LC	4.82	0.54	135	S3	0.58 - PC3	137 - PC3	S3
RAC4	RA-PC3-MS-MC	4.30	0.52	150	S3	0.58 - PC3	137 - PC3	S3
RAC5	RA-PC3-HS-LC	4.30	0.56	140	S3	0.58 - PC3	137 - PC3	S3

The differences in compressive strength of PCs and their corresponding RACs at different ages is shown in Figure 5-13 in percentages. According to this figure, the compressive strength increment varies for different types of RAC at different ages. While RAC2 showed almost 90% higher compressive strength in compassion with its corresponding PC (PC2) at 7 days, RAC1 with higher targeted compressive strength behaved differently. Correlation between the compressive strength of RAC at 28 days and 91 days with compressive strength of PCs, is strongly linear (see Figure 5-14). However, the correlation between 7-day compressive strength of RAC and compressive strength of PC seemed to be far from linear. It suggests the influence of other existing parameters and the possible interaction of different variables which have impact on the 7-day compressive strength of RAC. For example, the surface of RA, are usually partially carbonated. It could increase growing of new hydration products in the initial time of hydration and could cause the fast setting of RAC[15]. Assuming that the carbonation resistance of PC could have direct effect on the carbonation resistance of RA, it would be interesting to study the relation between the carbonation resistance of PC and extra achieved strength of RACs at 7 days (see Figure 5-15- red data points). A good correlation between two mentioned parameters suggests that carbonated surfaces at different levels could be one of the reasons for various achieved early strength of different types of RAC in this study.

On the other hand, in the fresh concrete made with RA, high porosity and water permeability of RA cause them to take up large amount of water during the initial mixing stage and thus decreases the initial w/c ratio in the ITZ at early stages of hydration. For production of RAC the right amount of w/c ratio in the ITZ is a key. Investigations show that the old paste in ITZ can provide additional active ingredient such as Ca $(OH)_2$ which provides a better hydration environment and more number of C-S-H can be generated[4]. It is known that water permeability and compressive strength of concrete have an inverse correlation[1]. Assuming RA to inherit the same properties as their PC, it would be interesting to check if increase in compressive strength (which means decreasing the water permeability) of PC decreases the achieved early strength of RAC. High inverse correlation between compressive strength of PC and early achieved strength of RAC in Figure 5-15- blue data points indicates the strong direct effect of PC water permeability on the early strength of RAC. Considering different concrete trials carried out during C2CA process development[1,2], it is concluded that using a modified recipe for RAC based on the utilization of the same amount of cement and consistence (as it is in PCs) create faster setting time. Due to this unique properties, the recycled aggregates are particularly suitable to be used in the prefab elements production.

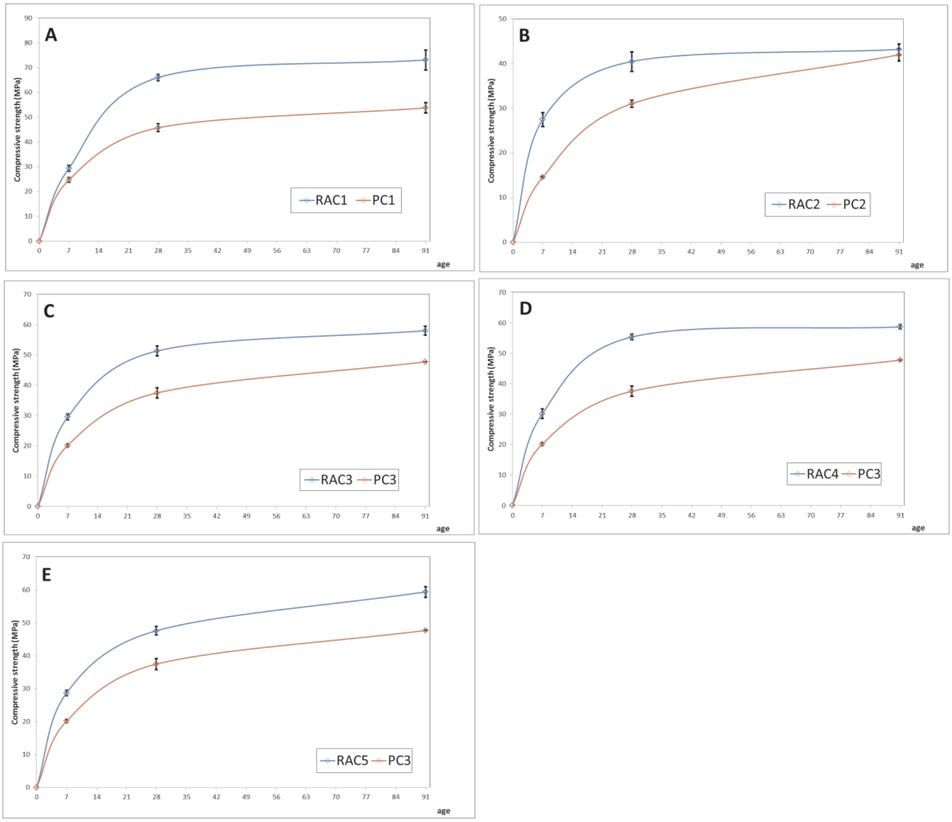

Figure 5-12: Comparison between compressive strength of RAC(—) and PC (—) in different ages.

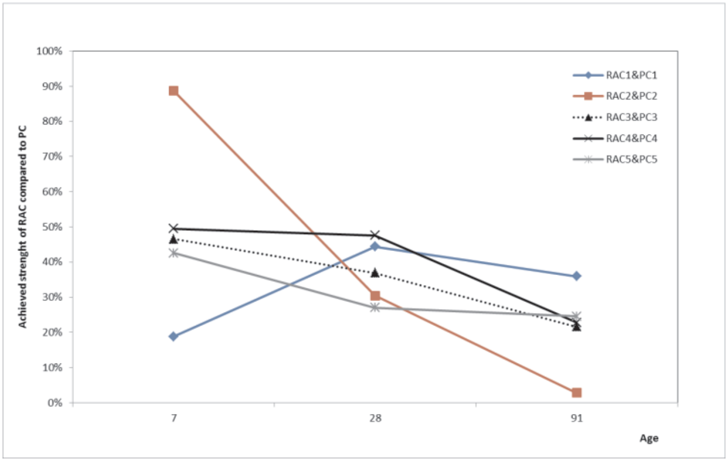

Figure 5-13: Extra achieved compressive strength of RACs compared to PCs at different ages.

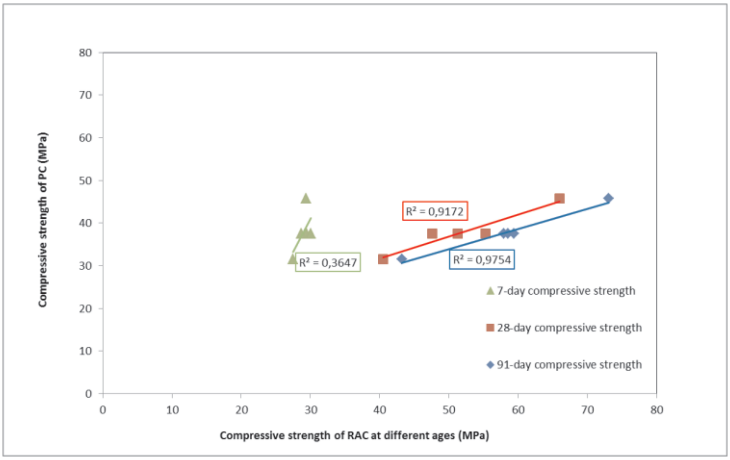

Figure 5-14: Comparison between compressive strength of PC and RAC samples at different ages.

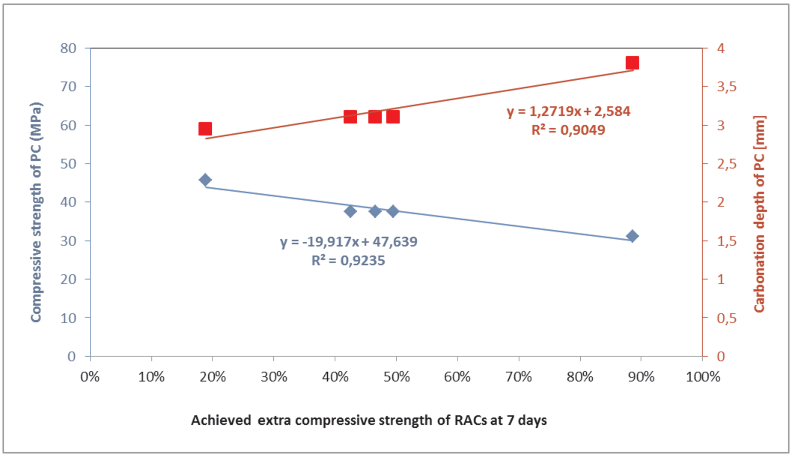

Figure 5-15: Correlation between extra achieved compressive strength of RACs at 7 days with carbonation depth and compressive strength.

5.5.2 Durability properties of RAC

For evaluating the durability of RAC with respect to the considered recycling variables, carbonation depth, water absorption and freeze-thaw resistance tests were carried out. Table 5-9 shows the depth of carbonation in RAC and PC samples, under controlled exposure conditions.

Table 5-9: Comparison between carbonation depth of RAC and PC.

Average carbonation depth[mm]				
RAC code	RAC 56 Days	RAC 90 Days	PC 90 Days	PC Code
RAC1	1.02	1.18	2.95	PC1
RAC2	6.58	6.99	3.8	PC2
RAC3	3.99	4.31	3.1	PC3
RAC4	3.79	4.09		
RAC5	4.20	4.63		

Considering the carbonation test results, first of all RAC1 presented a better carbonation resistance in comparison with other samples. The lower w/c ratio in RAC1, enhances durability due to a much denser matrix. The use of superplasticizer improves the carbonation performance of concrete, since it leads to a reduction of the effective w/c ratio, which results in a decrease of porosity and CO_2 permeability[16].

Pedro et al. reported that the carbonation depth increases with decrease of the concrete's target strength[17]. It corresponds well with the observations in this study (see Figure 5-16 and Figure 5-17). It is also known that the permeability of concrete is a crucial factor affecting the carbonation resistance[18]. The rate of most kinds of concrete deterioration depends on concrete permeability. This is because water absorption is indirectly related to permeability of hardened concrete, and penetration of water into concrete is required for most deterioration mechanisms to be effective[19]. Table 5-10 shows the water absorption of RAC samples. From this table it is clear that RAC2 has the highest amount of water absorption due to low compressive strength and its mix design. A good correlation between carbonation depth, water absorption, compressive strength and w/c ratio of concrete samples, indicates that regardless of the effect of RA, concrete mix design is a crucial factor. On the other hand, results of carbonation test show that even contributing both RA and RS (see sample RAC5), has minor detrimental effect on the RAC and the influence of concrete mix design on the carbonation resistance is more dominant (Compare RAC2 and RAC5 in Figure 5-18). All types of evaluated RAC in this study fulfil the water absorption criteria expressed in standards EN 1338, EN 1339 and EN1340 (water absorption less than 6.5%), while just RAC1 satisfies well the Polish standard PN-B 06250 which requires water absorption of less than 5% for concrete used in weather/environmental dangerous situations.

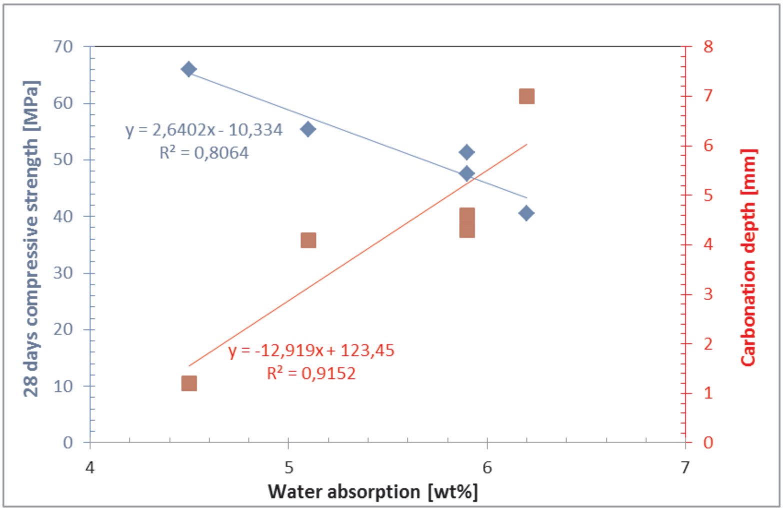

Figure 5-16: Correlation between water absorption and compressive strength and water absorption and carbonation depth of RAC samples.

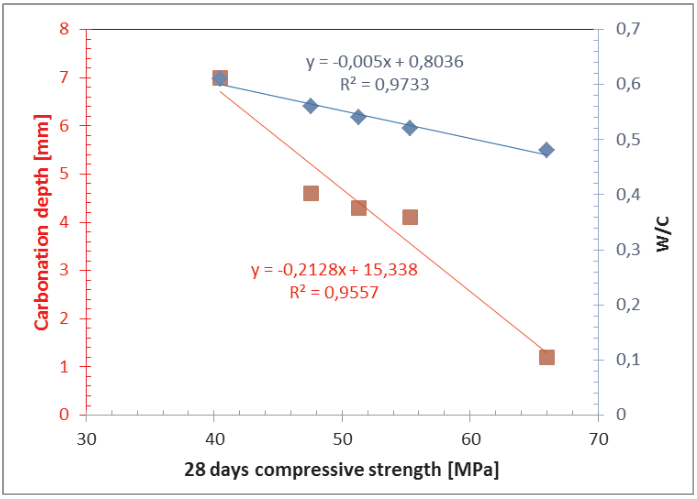

Figure 5-17: correlation between compressive strength and carbonation depth and compressive strength and w/c ratio of RAC samples.

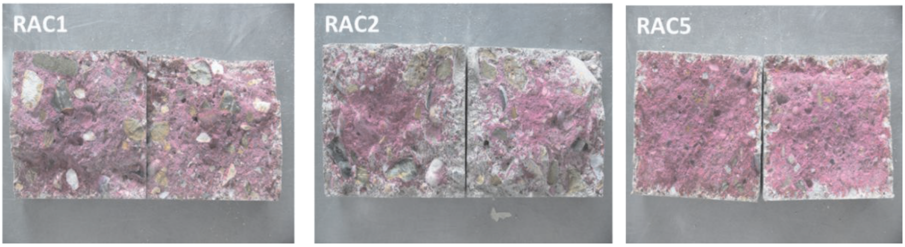

Figure 5-18: The impact of concrete recipe on carbonation depth.

Table 5-10: Water absorption of RAC samples.

RAC code	Average water absorption[wt%]	Standard deviation
RAC1	4.5	0.4
RAC2	6.2	0.2
RAC3	5.9	0.2
RAC4	5.1	0.1
RAC5	5.9	0.2

The freeze-thaw resistance test was carried out on PC and RAC samples and the results are shown in Table 5-11. From the results it is clear that in all cases RAC behaved better than PC. Although in some research it is reported that there is no significant difference in frost resistance of RAC and concrete made of NA, in many cases recycled mixes tested exhibited better durability than concrete made with virgin materials[20]. It corresponds well with the achieved results in this study. The difference in the freeze-thaw behaviour of the RAC and PC samples can be related to the differences in their compressive strength[1]. The freeze-thaw resistance test on RAC samples indicate that they can be classified as good according to the criteria from EN 1338.

Table 5-11: Scaled materials from RAC samples after freeze-thaw cycles and comparison between the total scaled materials from PC and RAC after the freeze-thaw test.

RAC code	Scaled material[kg/m^2]							
	7 cycles	14 cycles	28 cycles	42 cycles	56 cycles	Total scaled material		
						RAC	PC	PC code
RAC1	0.53	0.09	0.17	0.11	0.05	0.95	2.978	PC1
RAC2	0.44	0.29	0.30	0.19	0.11	1.33	9.644	PC2
RAC3	0.23	0.25	0.12	0.08	0.06	0.74	3.616	PC3
RAC4	0.21	0.18	0.15	0.06	0.05	0.65		
RAC5	0.32	0.29	0.17	0.04	0.03	0.85		

5.5.3 Discussion of the variables impacts

Figure 5-19 (A to I) summarizes the effect of milling intensity, ADR cut-size and PC recipe (indicating by PC's 28 days compressive strength) on durability properties of RAC. In this figure it is tried to show the effect of one experimental variable at a time, while keeping other variables constant. Considering the water absorption of RAC (Figure 5-19-A,D and G), it is clear that changing the milling intensity and type of PC have an influence. In general increasing the milling intensity and PC compressive strength will lead to a reduction in RAC water absorption (see Figure 5-19-A, B and C). On the other hand, carbonation and freeze-thaw resistance are affected by all three involved parameters in the recycling process. In general increasing both the milling intensity and compressive strength of PC have positive effect on durability properties of RAC. Considering the effect of ADR cut-size point, it is observed that the addition of recycled fines 2-4 mm slightly reduces both freeze-thaw resistance and resistance to carbonation (see Figure 5-19-E and F). However, the influence of ADR cut-size on the water absorption of RAC is neutral (see Figure 5-19-D).

Figure 5-20 (A to C) shows the influence of different recycling variables on the achieved compressive strength of RAC compared to PC at 7 days. From the figure it is clear that milling intensity and ADR cut-size have a moderate influence on the achieved strength. By increasing the milling intensity from HS-LC to MS-MC the achieved strength raises (see Figure 5-20-A). On the other hand, using 2-4 mm recycled sand has an inverse effect on the achieved strength (see Figure 5-20-B). The addition of ADR "fine" fractions slightly increased water demand of RAC5 (from 0.54 for RAC3 to 0.56 for RAC5). It probably resulted in slight reduction of initial compressive strength of RAC5. Before running the experiments it was assumed that the addition of the old hydrated mortar existing in ADR fines could cause a faster crystallization/hydration of the cement phases resulting in higher increment of the early compressive strength[4]. However, the results show that the water demand of the fines (higher w/c ratio of RAC5) prevents observing the mentioned effects. Increasing in the strength of PC, leads to a reduction in the achieved early strength (see Figure 5-20-C).

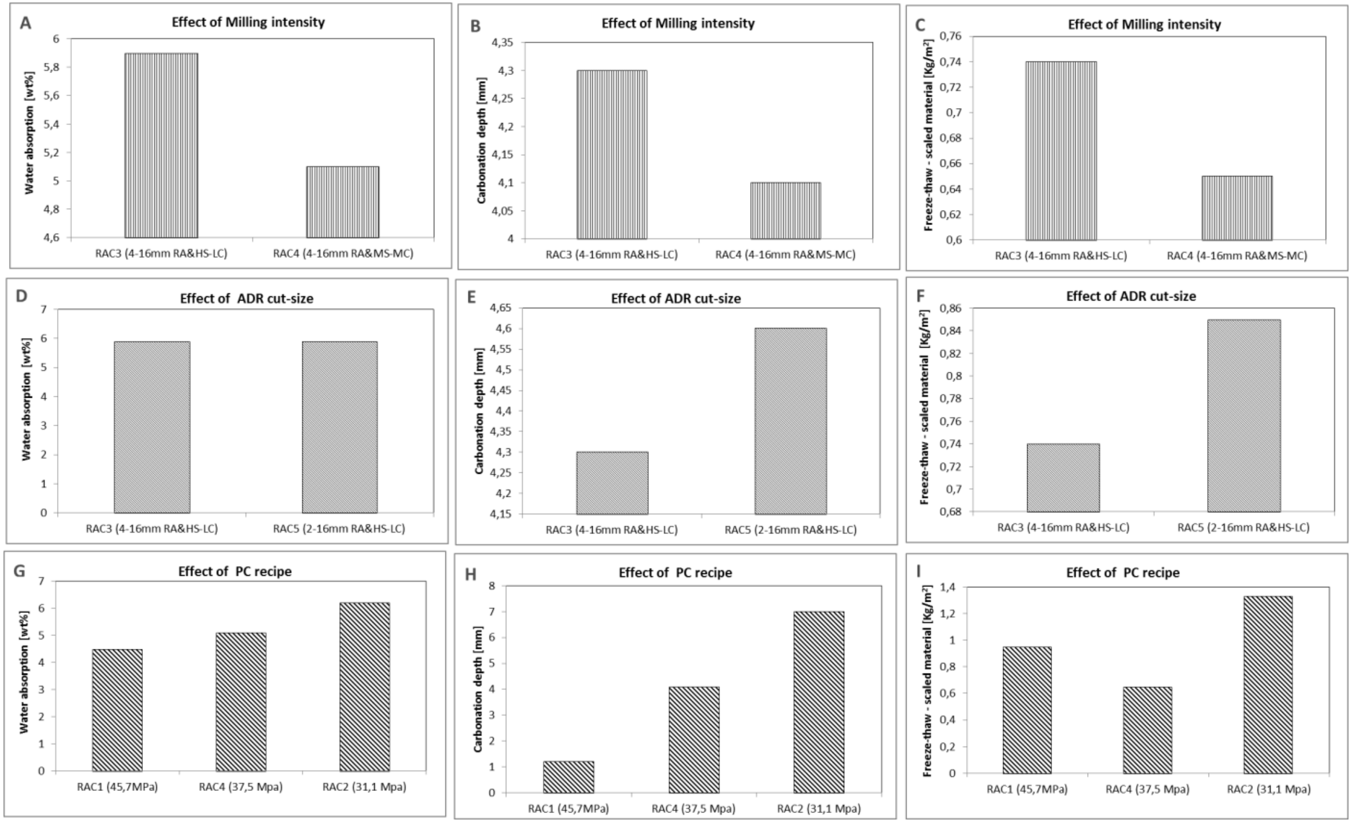

Figure 5-19: Effect of different recycling parameters independent of other variables on the durability of RAC.

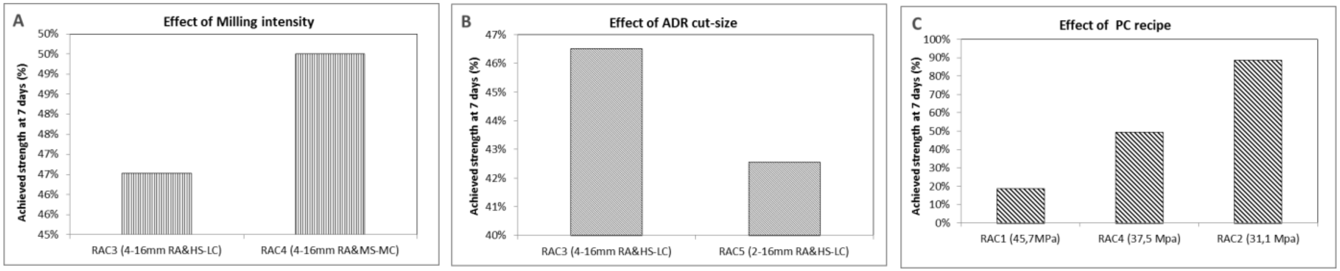

Figure 5-20: Effect of different recycling parameters independent of other variables on the achieved extra compressive strength at 7 days.

5.6 CONCLUSION

A new process for recycling of concrete to concrete (identified as the C2CA process) has been developed. This process aims at a cost effective system approach for recycling of EOL concrete into high-grade aggregates and low- CO_2 raw material for the cement production. The industrial process applies selective demolition, autogenous milling and ADR as key technologies to deliver cleaner recycled aggregate. Among various liberation routes, autogenous milling, offers low complexity (mobile) and low-cost technology to remove the fragile mortar from the surface of aggregates. After milling, ADR efficiently separates the moist material into fine and coarse fractions.
This paper investigates the effect of various factors during the C2CA recycling procedure on the quality of the produced RA and RAC. The aim is to get more insight towards fine tuning of this process. Concrete recycling experiments were conducted varying the milling intensity, type of parent concrete and ADR cut-size. Among various milling intensities, and assuming the existence of mixed types of concrete in CDW, milling at medium shear and medium compression appears to improve the quality of RA and the durability performance of RAC. Using ADR cut-size of 2mm delivered favourable results. However, in order to eliminate the adverse effect of contaminants that are mostly concentrated in ADR fines, more study is required. Compressive strength test results proved that RAC production using a modified concrete recipe (with no additional cement) lead to higher strength especially at early ages. Taking the advantage of the today's demand for the fast track work in construction industry and saving time for the prefab elements production, the aforesaid unique property of RAC would be a key to improve the social consciousness towards application of this valuable material.

5.7 REFERENCES

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CHAPTER 6

Assessment of contaminants level and removal from RA

This chapter is based on the published article:

Lotfi et al., Assessment of the contaminants level in recycled aggregates and alternative new technologies for contaminants recognition and removal, EMABM 2015.

6.1 ABSTRACT

One of the main challenging problems associated with the use of Recycled Aggregates (RA) is the level of mixed contaminants. For utilizing RA in high-grade applications, it is essential to monitor and minimise the content of the pollutants. To this extent the C2CA concrete recycling process investigates a combination of smart demolition, followed by new innovative technologies to produce high-grade secondary aggregates with low amount of contaminants. This chapter firstly reports the level of contaminants in different fractions of recycled aggregates coming from a real case study. Results show that the wood content of 4-16 mm recycled aggregates is well within the strictest limit of the EU standard. However, there are still large visible pieces of wood and plastic in the +16 mm RA fraction which, albeit within the standards, does not satisfy the users. In order to solve this problem the feasibility of applying two existing technologies (near infrared sensor sorting and wind sifting) to remove contaminants, is studied.

6.2 INTRODUCTION

The efficient high-grade recycling of Construction and Demolition Waste (CDW) is of increasing interest from an environmental and economic perspective. From an environmental point of view, the urgency of saving resources and reducing humanity's impact on the environment is evident. The need of increasing recycling and improving the quality and homogeneity of recycled materials to minimize environmental pollution and the use of primary resources is a topical subject for European Community (Enterprise and Industry reports of the EC).

In order to enhance the quality of RA for high-grade applications, the content of contaminants such as organic materials (wood, plastic and foams), gypsum and glass must be minimised[1]. Many organic substances such as wood are unstable in concrete when submitted to drying and wetting or freezing and thawing[2].Water-soluble sulphates (coming from gypsum plaster) in RA are reactive and may produce expansive reactions while structural concrete containing RA with high chloride content may deteriorate more rapidly due to the corrosion of reinforcement bars (RA coming from concrete subjected to marine may have high soluble chloride content)[3]. Plate glass from windows has the density similar to the stone's and brick's and therefore it complicates its separation. Thus pre-sorting of the glass is essential also because of the alkali- silica reactions which can take place due to non-crystalline metastable silica[2].

Considering the importance of upgrading the quality of the RA and removing the contaminants, currently different technologies and procedures such as smart demolition and dismantling of End-Of-Life (EOL) buildings, automated sensor sorting and online quality control sensors have been developed[4,5,6]. A novel concrete recycling process developed within an European funded project[7], aims at a cost-effective system approach for recycling high-volume EOL concrete streams into high-quality aggregates and cement. The best practices and technologies implemented are smart demolition to produce crushed concrete with low levels of contaminants, followed by mechanical upgrading of the material on-site into an aggregate product and a cement-paste concentrate that can be processed (off-site) into a low-CO_2 input material for new cement production. Sensor-based on-line quality assurance allows for a proper monitoring of the output. Achieving in-situ recycling of the EOL concrete is one of the main goals of this process. Therefore, the liberation of the cement paste as well as the sorting and size classification of the aggregate, is performed purely mechanically and in the moist state, i.e. without prior drying or wet screening. This choice reduces process complexity and avoids problems with dust or sludge while providing economic benefits in terms of process costs and logistics. After crushing, liberation of the cement paste is promoted by several minutes of grinding in a small-diameter (D = 2.2 m) autogenous mill and at the same time producing as little as possible fine silica. Then a new low-cost classification technology, called Advanced Dry Recovery (ADR) is applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles. ADR uses kinetic energy to break the bonds that are formed by moisture and fine particles and is able to classify materials almost independently of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. ADR separation has the effect that the input aggregate is concentrated in two main streams: a coarse aggregate product and a fine fraction which includes the cement paste and contaminants (e.g. wood, plastics and foams).

In the current study, the influence of different recycling steps in C2CA process in the level of contaminants is investigated and solutions to make clean final products are presented. The aim is to enrich our understanding of the importance of existing recycling steps with respect to eliminating the contaminants in recycled aggregate.

6.2.1 End of life building (case study in Groningen)

The case study of the C2CA project involved the demolition of a governmental complex in the province of Groningen in the Netherlands and the building of an underground garage from concrete with recycled aggregate. The scope of the demolition part of the project mainly consisted of two identical high-rise towers (KB2 and KB6) with the blue dotted line in Figure 6-1. The section plan of the towers can be seen in Figure 6-2. Figure 6-3 shows the general layout of the C2CA technology with different steps for contaminants removal.

6.2.2 Smart dismantling and selective demolition

An EOL building may be conventionally or selectively demolished. Although the construction and demolition industries still see the concept of the selective demolition doubtful from economic point of view, it may be more profitable than the conventional demolition approach and the most effective way of minimising the amount of contaminants in CDW materials[8].

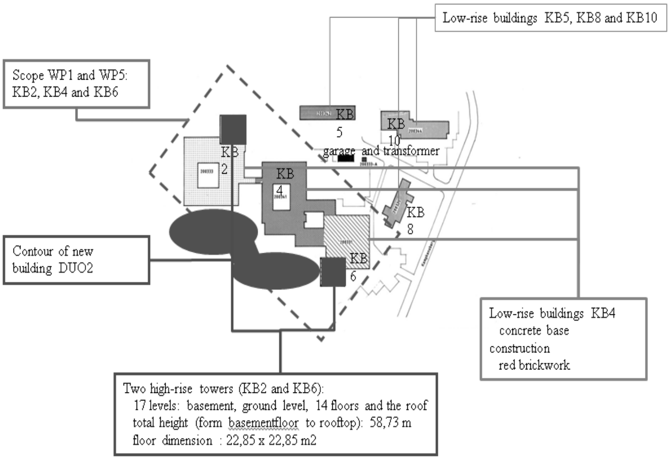


Figure 6-1: Overview of the end of life buildings.

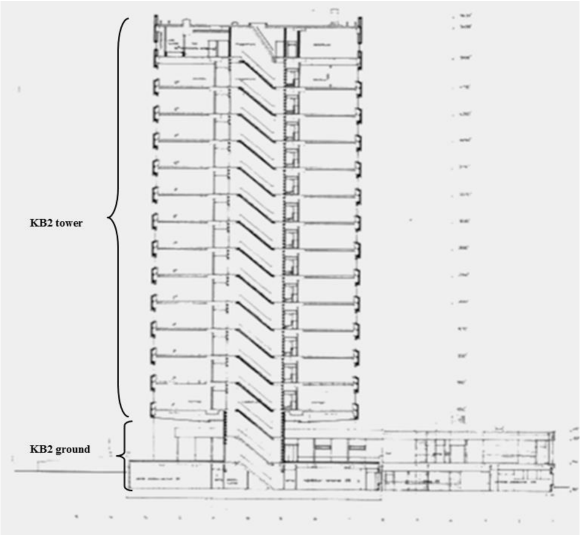


Figure 6-2:Section plan of the EOL building.

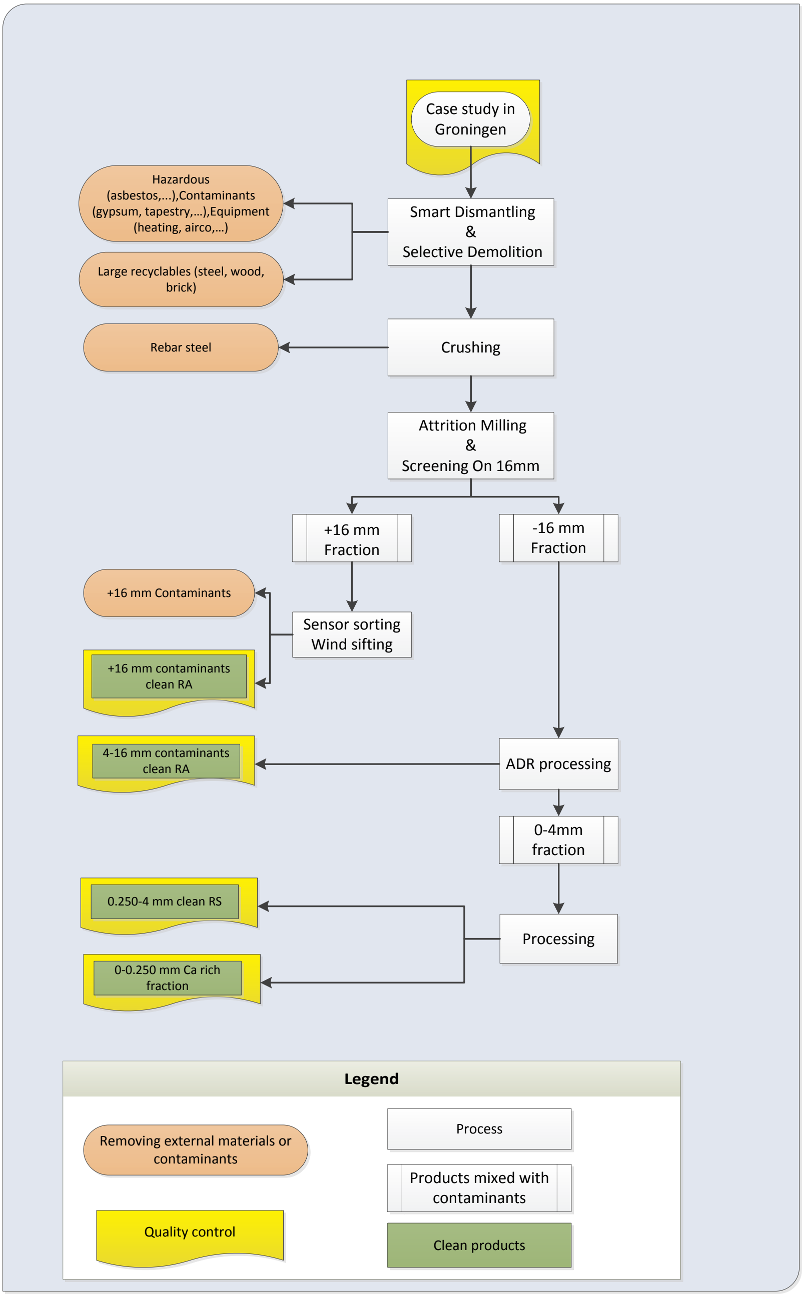


Figure 6-3: General layout of the C2CA technology showing different steps for contaminants removal. Two sensors (HSI and LIBS) are being developed for the quality control of products.

In the 70's and 80's the Dutch construction sector used asbestos in the buildings. Therefore prior to the dismantling and demolition of KB2 and KB6 buildings, asbestos was removed and collected in the total amount of 40 tons. The further strategy for the dismantling of the KB2 and KB6 involved the detailed removing of all materials from the concrete skeleton before starting the demolition: air-conditioners, radiators, lamps, piping systems of water and heating, electric cables, carpets, gypsum plates from ceilings and walls, window glass, frames of doors and windows etc. For the demolition, two methods were applied: the top-down method to demolish the top 12 floors, and short-reach method to demolish the lowest 2 floors of the towers. The materials composition of KB2/KB6 tower can be seen in Figure 6-4. It demonstrates that the amount of EOL concrete was 87wt% of the whole CDW materials.

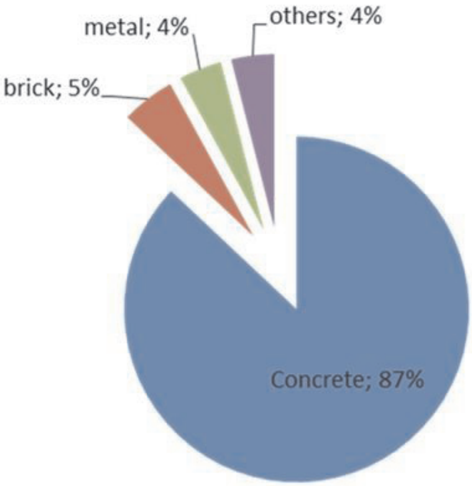


Figure 6-4: Material composition (wt%) of KB2/KB6 tower.

6.2.3 Crushing and constituent of the crushed EOL

EOL concrete coming from smart dismantling and demolition was subjected to a primary crushing to break the materials down to 40 mm size. After crushing and removing ferrous metals by means of magnetic belts, the constituents of the crushed EOL concrete was determined by hand picking. In order to facilitate the hand picking procedure a big bag of crushed EOL concrete with the weight of approximately 1 ton was screened on 20 mm, 10 mm and 5 mm sieves. Sampling of each fraction was carried out in accordance with the standard (EN 932-1) and the contaminants were hand-picked from fractions bigger than 5 mm.

Results show that a +5 mm crushed EOL concrete coming from C2CA case study, consists of 99.32wt% clean crushed concrete and 0.68wt% of the mixed contaminants. Figure 6-5 shows the constituents of the contaminants mixed with concrete. From the results, it is obvious that smart dismantling is mostly effective for reduction of gypsum to very low amount of almost 60 ppm. The measured level of wood in crushed EOL concrete satisfies FL_2 level of the EU standard (EN 12620). However, it is still high (most contaminated sample contained~2 cm^3/kg of floating). According to the developed specifications which include a definition for RA, the minimum amount of concrete (cement plus natural aggregate) should be 90% by mass[3]. Results of the hand picking test indicate that EOL concrete coming from smart dismantling and demolition satisfies those specifications in terms of mixed contaminants. However, since customers demand even smaller amount, complementary technologies to eliminate them are needed.

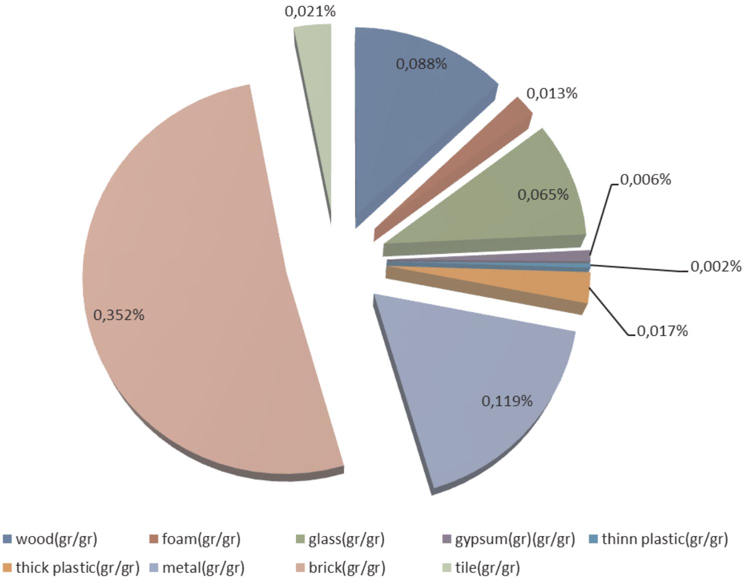


Figure 6-5: Constituents of the contaminants mixed with concrete.

6.2.4 Autogenous milling

Autogenous milling of the crushed End of Life (EOL) concrete is a mechanical method to remove cement paste from the surface of aggregates. During autogenous milling, the combination of shearing and compression forces, promotes selective attrition and delivers a better liberation of cement. Beside liberation of cement, the acting forces could affect the size of the contaminants. In this regard, a batch test with around 15 tons of crushed EOL concrete was carried out. The residence time of the materials inside of the mill was estimated as 12 minutes. About 2 tons of sample from both mill input and output was taken in order to analyse the constituents. Samples were portioned to 5-10 mm, 10-20 mm and +20 mm fractions and their contaminants were hand-picked according to the procedure previously explained.

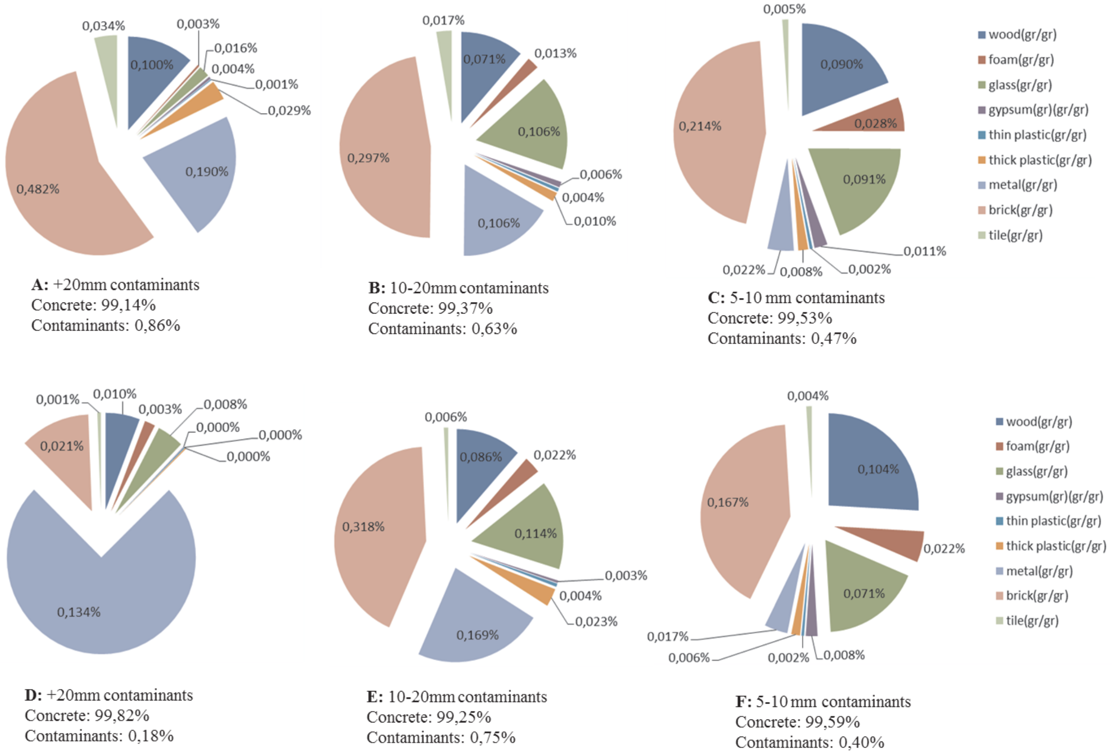
Figure 6-6 shows the mass percentage of the hand-picked contaminants from mill input and output for three aforesaid fractions. Considering the results after milling, the mass of contaminants (bigger than 5 mm) is reduced by 30%. It appears that by milling, contaminants are broken down in smaller parts so that the less than 5 mm fraction increases. There is a clear effect of the milling also on the size reduction of brick (compare Figure 6-6-A with Figure 6-6-D). A similar trend can be seen for wood contaminants albeit in a less outstanding way. In general it is observed that milling has an obvious effect on the size reduction of brick and a slight effect on size reduction of other contaminants.

6.2.5 Screening and ADR processing

In the C2CA concrete recycling process, autogenous milling of the materials is followed by a 16 mm screen and an ADR. Materials smaller than 16 mm are fed into the ADR and using a jet, the fines (0-4 mm) are separated from the coarse particles. The air knife installed in ADR helps to concentrate contaminants like wood, foam and plastic in the fines. In order to figure out the amount of wood in the coarse ADR products (4-16 mm RA) a sink floating test on approximately 1700 kg of RA and according to EN 12620 (for application of the material as coarse recycled aggregate) was carried out.

Result shows that the total amount of floating wood in 4-16 mm RA is almost 0.117 cm^3/kg which is well within the strictest norm of EU standard (EN 12620). ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product and a fine fraction including the cement paste and contaminants such as wood, plastics and foams (see Figure 6-7-B). ADR fines can be used as the input of cement kilns so that the wood and plastics contaminants are even beneficial for the process.

During the first C2CA case study, it became clear that because of the contamination, the +16 mm fraction does not have the market potential as such (see Figure 6-7- left). Therefore it would impair the economic attractiveness of the recycling process being developed. According to the visual evidence, there are big contaminants of wood and non-ferrous metals in +16 mm oversize fraction. In order to satisfy the customers' demands and use +16 mm RA for high-grade applications, contaminants should be removed from this fraction. Since +16 mm RA is a small stream (almost 30wt% a sensor sorter could be a cost effective option to clean this fraction. In this regard, the possibility of applying Near Infrared (NIR) sensor sorting technology to clean +16 mm RA was examined.



A: +20mm contaminants
Concrete: 99,14%
Contaminants: 0,86%

B: 10-20mm contaminants
Concrete: 99,37%
Contaminants: 0,63%

C: 5-10 mm contaminants
Concrete: 99,53%
Contaminants: 0,47%

D: +20mm contaminants
Concrete: 99,82%
Contaminants: 0,18%

E: 10-20mm contaminants
Concrete: 99,25%
Contaminants: 0,75%

F: 5-10 mm contaminants
Concrete: 99,59%
Contaminants: 0,40%

Figure 6-6: A, B and C show the amount of contaminants in the +5mm input of the autogenous mill. D, E and F show the amount of contaminants in the +5mm output of the autogenous mill.

Figure 6-7: Left) +16mm RA which still contain contaminants, Right) ADR fines in which light contaminants like wood and foam are concentrated.

6.2.6 NIR sensor sorting and wind sifting to remove contaminants from +16mm RA

Advanced automated sensor-based sorting technologies use physical – chemical properties of different materials such as density, electrical conductivity or magnetic susceptibility, as well as surface and material properties, such as NIR spectrum or the visible colour[1].For this part of study, NIR sensor sorting facility of TOMRA GmbH sorting in Germany was used (Figure 6-8 shows the functional principle). Input material (1) is evenly fed onto a conveyor belt, where it is detected by the NIR and/or VIS spectrometer (2). If the sensors detect material to be sorted out, it commands the control unit to blow the appropriate valves of the ejection module at the end of the conveyor belt. The detected materials are separated from the material flow by jets of compressed air. The sorted material is divided into two or three fractions in the separation chamber (3). For testing the performance of the NIR sensor sorting system, around 900 kg of +16 mm of crushed concrete was delivered to TOMRA sorting GmbH. During the experiment, contaminants (wood, plastic and metal) with size of 10-20 mm and +20 mm were added to the clean crushed concrete. The output of the NIR sensor sorting system consists of an accepted portion (clean concrete) and ejected contaminations. Figure 6-9 shows an example of the input contaminants to the NIR sensor sorting system and accepted and ejected outputs. The process flow diagram for 20 t/h/m of the throughput shows that by using NIR sorting, almost 88% mass% of wood is thrown out and small pieces are left in the product. Plastic and metal are also removed (see Table 6-1 and Table 6-2).

The investment cost of a NIR sorting system (including high speed conveyor and separation chamber) vary depending on the width of the system between approximately €95,000 (0.6 m width) to roughly €230,000 (2.8 m width). Considering the investment costs for other equipment which are needed to operate a NIR sorting system (compressor, cables, electrical equipment, conveyors for output fractions, installation) total investment cost would be €140,000 (0.6 m wide system) and €320,000 (2.8 m wide system). It is estimated that for a 2 meter width of the belt (40 t/h), with running time of 1600 hours/year the cost of processing will be 1.2 euro/ton.

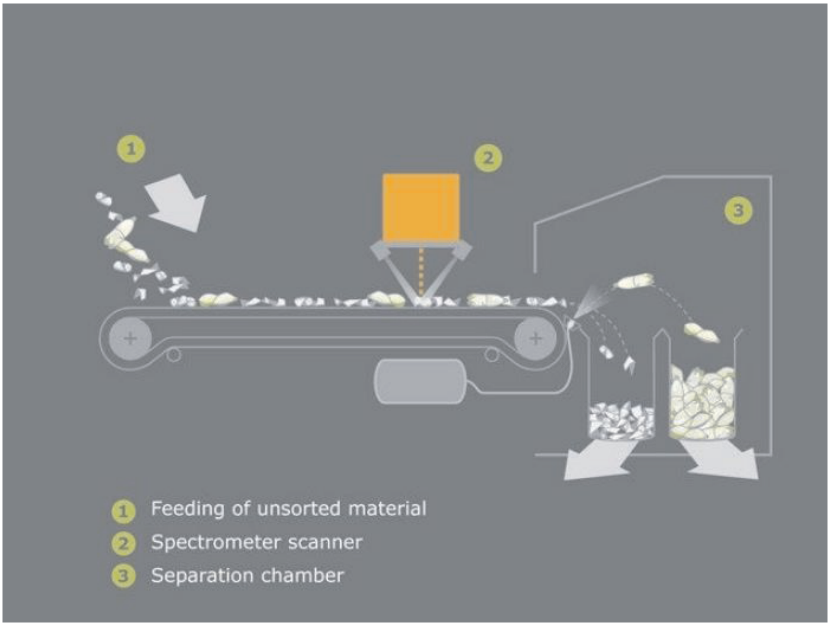


Figure 6-8: Functional principle of NIR sensor sorting technology[TOMRA].

A: Example of input contaminants to the NIR sensor sorter, B: Accepted materials (NIR sensor sorting out put), C: Ejected materials (NIR sensor sorting out put)

Figure 6-9: Input contaminants and accepted and ejected output of NIR sensor sorting system.

Table 6-1: Mass analysis of NIR Input.

Materials	Weight(gr)	Mass%
Clean crushed concrete	278000	99.87%
Wood	230	0.08%
Plastic	121	0.04%
Total	278351	100%

Table 6-2: Mass analysis of NIR output.

Materials	Weight(gr)	Mass%
Crushed concrete in accepted materials	267900	96.24%
Crushed concrete mixed in ejected materials	10136	3.64%
Wood in ejected materials	203	0.07%
Plastic in ejected materials	123	0.04%
Total	278362	100%

Considering the above mentioned results, the only limitation with NIR sensor sorting system is its current inability to remove small contaminants which therefore remain in the accepted output. To reach a more accurate contaminants removal, the combination of the wind sifting technology with NIR sorting is considered beneficial. In this regard, a test was carried out to examine the performance of a wind sifter to remove plastic and wood. The test was performed at REDOX B.V. in the Netherlands (see Figure 6-10). The input materials of the wind sifter consisted of almost 500 kg of +16mm crushed concrete mixed with a specific amount of wood and plastic.According to the process flow diagram (see Table 6-3 and Table 6-4), it is concluded that wind sifting is able to remove 80% (by number) of wood and plastic contaminants from the stream (for 35t/h throughput). Big particles which are heavier cannot be removed and remain in the final products. In Figure 6-11 the remained big pieces of wood in the final product can be seen.

The investment cost of the REDOX wind sifter is 75000 euro. It is estimated that for a 40 t/h throughput, with running time of 1600 hours/year the cost of wind sifting process will be 0.1 euro/ton.

Figure 6-10:Wind sifting facility in REDOX.

Figure 6-11: Input of wind sifter (upper images) which consists of wood, plastic and clean +16 mm crushed concrete. Images at the bottom demonstrate the removed wood and plastic using wind sifter and remained wood in the products.

Table 6-3: Mass analysis of the wind sifter Input.

Input	Weight(gr)	Mass percentage	Number of particles
clean crushed concrete	524000	99.90%	-
wood	324	0.06%	134
plastic	195	0.04%	48
total	524520	100%	-

Table 6-4: Mass analysis of the wind sifter output.

Output	Weight(gr)	Mass percentage	Number of particles
crushed concrete in accept materials	513390	97.88%	-
crushed concrete in eject	10790	2.06%	-
wood in eject	209	0.04%	107
plastic in eject	130.6	0.02%	39
total	524520	100%	-

6.3 CONCLUSIONS

According to the results the following conclusions can be drawn out:

- Smart dismantling and selective demolition is the most important step to minimise contaminants in RA. Results show that although the wood content of 4-16 mm recycled aggregates is well within the strictest limit of the EU standard, the still visible pieces of wood and plastic in the +16 mm RA fraction reduces the economic potential of the RA. Using selective demolition in this study, the amount of gypsum and wood in the crushed EOL concrete was reduced to almost 60 ppm and 2 cm^3/kg respectively.
- Autogenous milling reduces the mass percentage of contaminants bigger than 5mm by 30%. There is a clear effect of the milling on the size reduction of brick. A similar trend can be seen for wood contaminants but in a less outstanding way.
- The amount of wood in 4-16mm ADR product was measured as 0.117 cm^3/kg which is well within the strictest norm of EU standard.
- It is revealed that the combination of two technologies (NIR sensor sorting and wind sifting) will remove most of the contaminants from +16 mm RA.

- Two sensors (LIBS and HSI), presently in development, should allow online methods for quality control and quality assurance of the concrete recycling products. The concept is to avoid the need for laboratory analysis and intermediate storage and if possible quality and end- of-waste certification at the site without human intervention. Recent investigations related to the aforesaid sensors show their high potential towards achieving the mentioned goals.

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CHAPTER 7

Recycling of ADR fines into hardened cement and clean sand (HAS technology)

This chapter is based on the published article:

Lotfi S, Rem P, (2016), Recycling of End of Life Concrete Fines into Hardened Cement and Clean Sand. Journal of Environmental Protection, 7(06), 934.

7.1 ABSTRACT

One of the massive by-products of concrete to concrete recycling is the crushed concrete fines, that is often 0-4mm. Using this fraction into new concrete is detrimental, due to its high water absorption and mixed contaminants. Considering the shortage of natural resources and the goal of achieving sustainable developments, many studies have been performed on re-use of recycled concrete coarse and fines in new building materials. Although the construction sector is to some extent familiar with the utilization of the coarse fraction of crushed concrete, at present there is no high-quality application for crushed concrete fines. Here we present an effective recycling process on lab scale to separate the cementitious powder from the sandy part in the crushed concrete fines and deliver attractive products with the minimum amount of contaminants. This separation can facilitate the high-quality reuse of the hardened cement rich fraction in virgin cement production. This study aims to achieve preliminary information for designing an industrial scale recycling set-up for fines. Results show that by heating the materials to 500^{0}C for 30 seconds, the time of milling is diminished by a factor of three while the quality of the products satisfies well the market demand.

7.2 INTRODUCTION

The EU 28 countries currently generate 461 million tons per year of Construction and Demolition Waste (CDW) with an average recycling percentage of around 46%[1]. According to the revised Waste Framework Directive (WFD), the minimum recycling percentage of non-hazardous CDW should be at least 70% by weight by 2020[2]. End of life concrete is known to be the heaviest component of the CDW. By recycling part of the concrete fraction of CDW into high-quality construction materials such as aggregate, sand, and hardened cement, it is possible to get closer to the 2020 WFD goal. High-quality production and re-use of recycled aggregate is already well investigated and applied in countries like Netherlands, Belgium and Denmark[3]. Although concrete made with recycled aggregates is nowadays a practical reality in the building construction industry[4], the use of crushed concrete fines in new concrete production is still restricted in most standards. Crushed concrete fines is a massive fraction reaching the amount of 30 to 50 wt.% of the whole mass of crushed concrete[5]. However, due to high water absorption, low density and the presence of impurities, its application is presently limited. Thus, there is a need for a proper recycling process to liberate sand from hardened cement existing in crushed concrete fines and decrease contaminant concentrations as far as possible.

7.2.1 Current research background

A new technology of concrete recycling called C2CA (Concrete to Cement and Aggregate) aims at a cost-effective system approach for recycling high-volume End Of Life (EOL) concrete streams into prime-grade aggregates and cement (see Figure 7-1)[6].

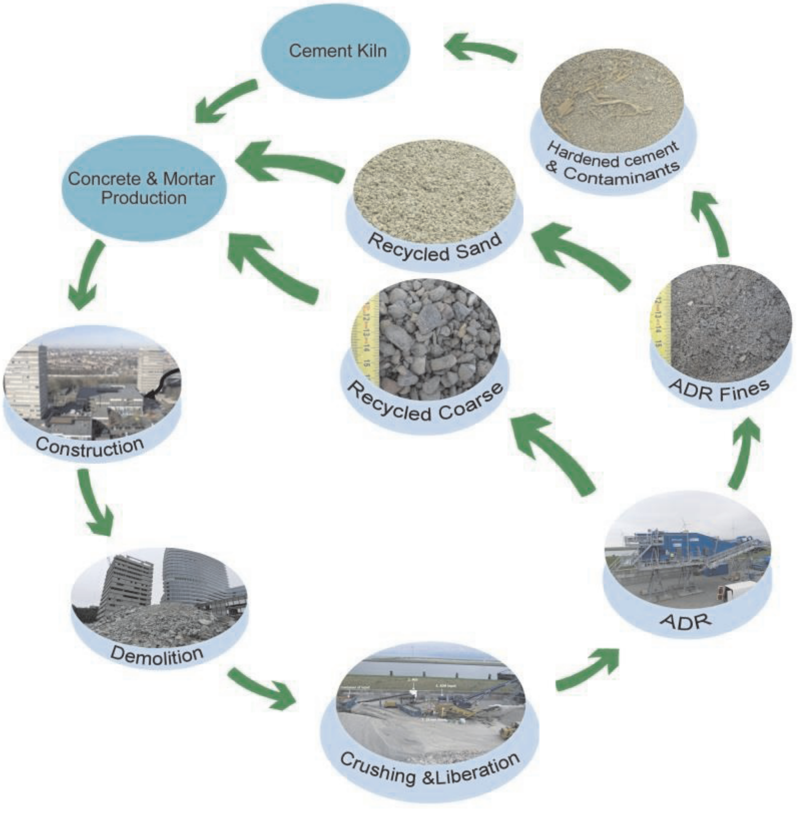

Figure 7-1: Complete loop of C2CA.

The C2CA technologies include selective demolition to produce crushed concrete with a low level of contaminants, and mechanical upgrading of the material on-site into an aggregate product with sensor-based on-line quality assurance and fines that can be processed (off-site) into Ca-rich material for new clinker production. In-situ recycling of the aggregate is one of the primary goals of the C2CA. In the C2CA process, after crushing of EOL concrete, autogenous milling is used to remove the loose mortar from the surface of the aggregates. The removal of the loose mortar is important to improve the mechanical strength of the recycled aggregate[7]. After autogenous milling, a new low-cost classification technology, called Advanced Dry Recovery (ADR) is applied to remove the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles. ADR uses kinetic energy to break the bonds that are formed by moisture and fine particles and can classify materials almost independent of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. ADR separation has the effect that the crushed concrete is concentrated into a coarse aggregate product and a fine fraction that includes the hardened cement, sand and light contaminants such as wood, plastics, and foams[6, 8] (see Figure 7-2).

Figure 7-2: Products from crushed concrete by ADR: Coarse (left) and Fine (right)[9].

To reduce cost and allow straightforward shipment of the produced recycled aggregate to a concrete production company, the C2CA technology develops two types of sensors, hyper spectral imaging and laser induced breakdown spectroscopy, for automated online quality control and quality assurance[6, 10-12]. The concept is to avoid the need for laboratory analysis and intermediate storage, minimize transport of bulk materials and combine, if possible, quality and end-of-waste certification at the site, without human intervention.

A second major goal of C2CA, next to in situ processing and local reuse of the aggregate, is to help decrease CO_2-emissions in cement production by concentrating part of the cement paste from EOL concrete into a separate fraction that can be reused as a low- CO_2 feedstock replacing primary limestone. The Portland cement manufactory process is presently responsible for a large part of the global emission of CO_2. It is estimated that the emission of carbon dioxide is at best around 0.87 ton for every ton of cement produced and the cement industry accounts for ca 10% of annual manmade CO_2 emissions[13]. In this regard, there have been recently some attempts to use crushed concrete fines or ADR Fines (AF) as alternative low CO_2- content input materials for the clinker production[14-16]. Within an industrial trial of the C2CA project for example, 600 tons of AF was successfully utilized in the industrial cement kiln of Heidelberg cement in the Netherlands to produce Portland cement. It is reported that the average amount of CaO and SiO_2 in the utilized AF were 11.7% and 75.5% respectively. Although the produced cement from this trial was ranked as a high-quality one, still the goal of substantial CO_2 reduction by replacing limestone with fines is not achieved. In the mentioned industrial-scale experiment, the maximum usage rate of AF was limited to 3.9 wt.% due to its high sand content.

In a recent study, Schoon et al[14] used AF as alternative raw material for Portland cement clinker production. They also confirmed that AF could be used primarily as SiO_2-sources in the cement kiln and by producing fines with higher CaO content it is possible to use it as limestone replacement. They demonstrated that the smaller fines fraction is cut from sand fraction, the better they are suited for Portland clinker production. Kwon et al.[16] and Gastaldi et al[15] used hardened cement waste for new clinker production. In their experiments, they managed to make clinker applying hardened cement waste as low CO_2 input material for the kiln. However, in both investigations it is concluded that an effective separation technology of cementitious powder from sand in crushed concrete fines is required.

AF contains hardened cement, unliberated pieces of sand, moisture and light contaminants such as wood. In fact, the main problem with crushed concrete fines is associated with its contaminated and moisturized nature that also applies for AF. The wet state of AF makes any dry separation process like screening or ball milling inefficient and costly while the contaminated nature of AF is the main concern for reusing it into new concrete. To deal with these problems, the C2CA project aimed to develop a combination of simultaneous heating, grinding and separation process in a fluidized bed to produce two main products: clean, dry sand ready for using in the concrete production and a concentration of cementitious powder with a very low amount of contaminants ready to sell as a minerals resource to the cement production companies.

The present study focuses on the lab-scale recycling of ADR fines (0-4mm) to hardened cement and sand using a combination of heating, air classification and grinding. Understanding the influence of heating temperature and grinding time on the hardened cement recovery is necessary for designing an industrial set-up for recycling of fines. This paper reports the effects of the process variables on the cement recovery, quality of the products and the level of the contaminants.

7.3 MATERIALS AND METHODS

7.3.1 0-4 mm ADR Fines(AF)

The 0-4 mm ADR Fines (AF) were produced in a case study of the C2CA project that involved the demolition of a part of a governmental complex constructed from concrete based on CEMIII cement. Recycling of the EOL concrete from the complex was performed applying C2CA technologies and the resulting AF was stored for further studies. The particle size distribution of 0-4mm AF was determined through dry sieving (see Figure 7-3). The moisture content of AF was 12wt.%.

7.3.2 AF Recycling set-up

The research set-up consists of a Heating-Air classification System (HAS) followed by grinding of materials using a Ball Mill (BM). HAS is made of an inclined pipe with a length of 600 mm (see the schematic of HAS in Figure 7-4). The internal and external diameters of the pipe are 11mm and 20mm, respectively, and it is covered by a steel lid to avoid the dispersion of heat. For heating, three burners with a flame temperature of 1410 °C were used. The temperature inside the pipe was measured by three thermocouples connected to a computer.

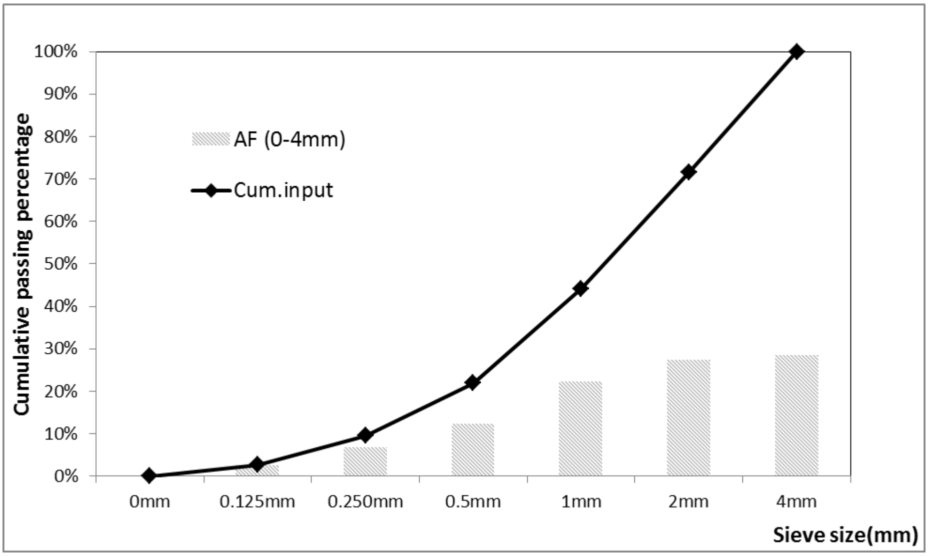

Figure 7-3: Particle size distribution of 0-4mm ADR Fines (AF). The line shows the cumulative curve whereas the bar indicate the absolute fraction weight.

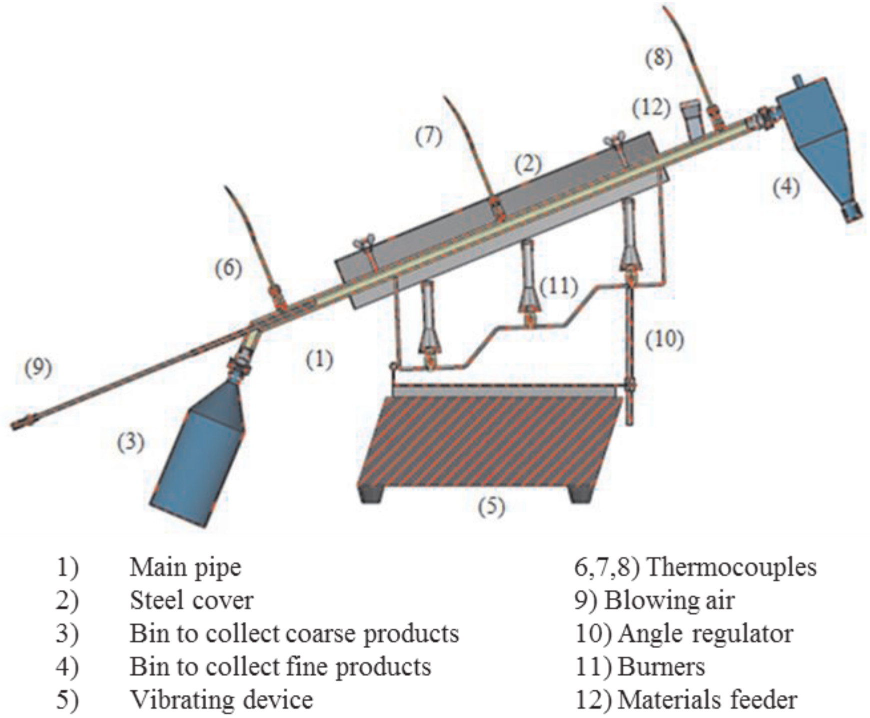

Figure 7-4: HAS set-up to heat AF and separate finer fraction (0-0.250mm) from coarser fraction (0.250-4mm).

To separate Finer Fraction(FF) which is mostly 0-0.25mm from the Coarser Fraction (CF) which is mostly 0.25-4mm, air classification is applied from the downer opening of the pipe. Thus, FF and light contaminants can be collected in a bin connected to the upper part of HAS. CF is led to a container connected to the down part of the pipe, and the whole system is installed on a vibrator to facilitate the materials movement inside the pipe.

After heating the materials, the produced CF is milled using a ball mill. The ball mill used in this study has a mill chamber with a diameter of 600mm and length of 300mm. The rotation speed was fixed at 45 rpm. Steel balls were put into the mill chamber to enhance the liberation of sand from cement powder. The balls to materials weight ratio was 2.5 and the diameter of the balls varied from 10 to 22 mm (see Figure 7-5).

Figure 7-5: Applied lab-scale ball mill (A) and steel balls (B).

7.3.3 Experimental Design

Experimental runs were carried out with varying temperature in HAS and residence time in BM. A variation of milling time and temperature resulted in a total of 20 different experimental conditions. Figure 7-6 gives a general overview of the recycling process.

7.4 RESULTS AND DISCUSSION

7.4.1 Heating-Air classification System (HAS) Performance

For each experimental run, firstly the desired temperature along the heating pipe in HAS was attained. As it was shown in Figure 7-4 three thermocouples connected to the burners register the temperature at different points of the pipe. To conduct the experiments, the intensity of the middle burner was varied to reach the target temperature of the experimental design. Residence time of the materials along the HAS pipe was 30 seconds. After processing of the materials at different temperatures, the performance of the HAS was evaluated. Results presented very small deviations in particle size distributions of FF and CF coming from different heating temperature. The particle size distributions of the AF and two outputs (FF and CF) of HAS at 750°C are shown in Figure 7-7 as an example. With the multiplication of the cumulative passing percentage of FF and CF to their total mass percentage, following by the summation of the results, it is possible to reconstruct the cumulative passing distribution curve for input materials (shown as the control curve in Figure 7-8). A comparison between the control and HAS-input curves in Figure 7-8, shows that a limited amount of liberation (production of new particles) happened during the HAS processing.

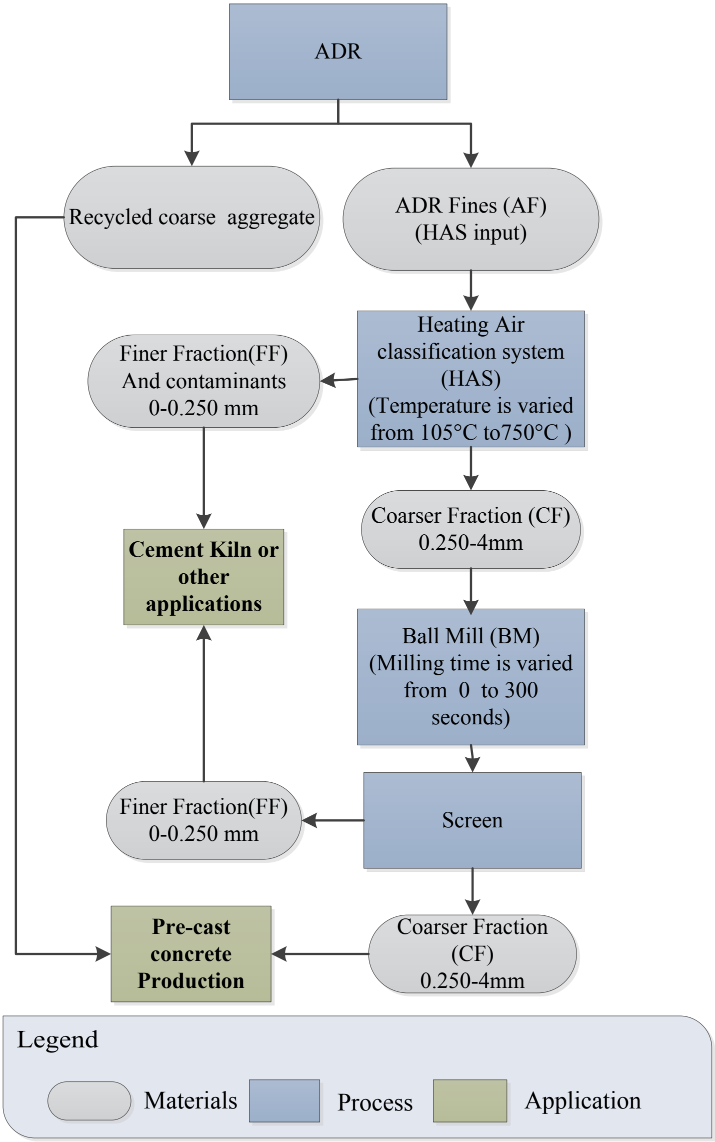

Figure 7-6: Flowchart of the recycling process.

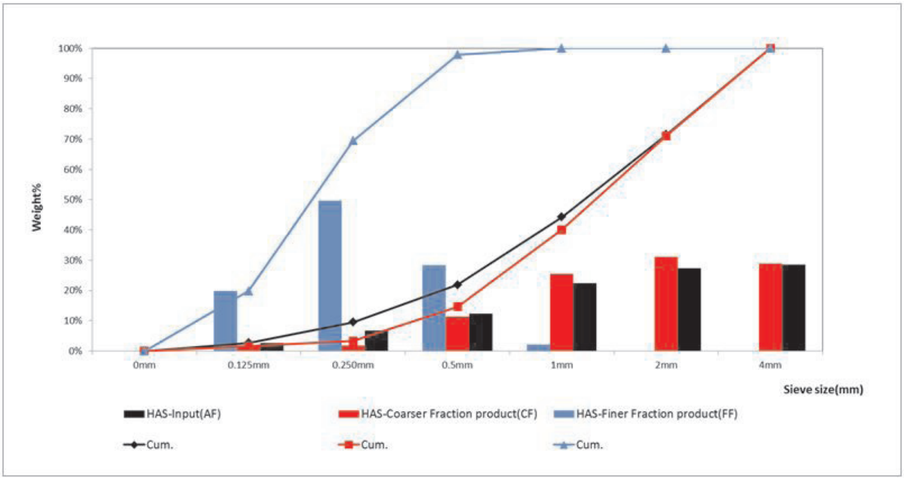

Figure 7-7: Particle size distribution of HAS input and outputs at 750°C. The lines show the cumulative curves whereas the bars indicate the absolute fraction weights.

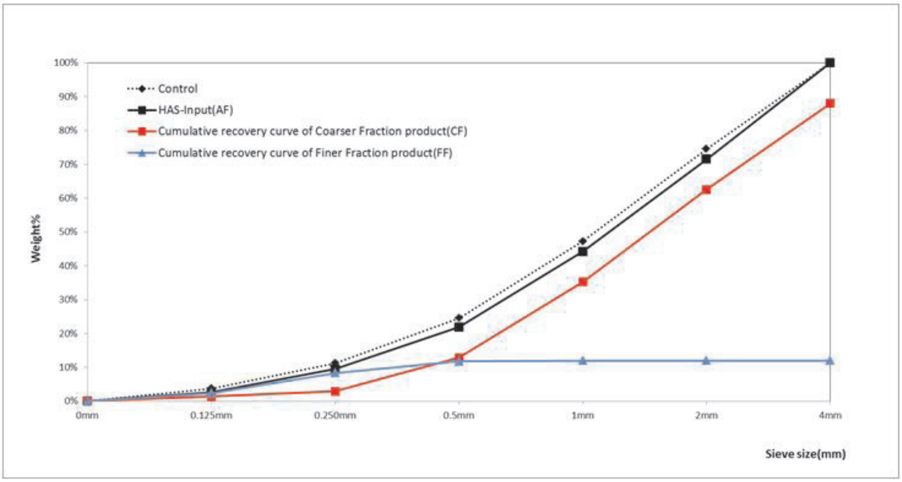

Figure 7-8: Reconstructed cumulative curve of the input materials (control curve) in comparison with the actual cumulative curve of HAS-Input.

The recovery of each size fraction in FF and CF and the cut size point is shown in Figure 7-9. According to the figures, it is clear that while HAS heats the materials, it efficiently uses the air flow to separate FF and light contaminants from CF (See Figure 7-10). When concrete waste is heated, dehydration of cement accrues which could weaken the bonding strength between cement paste and aggregate. Thus, the possibility of preferential breakage along the boundaries between aggregate and cement paste increases[17]. Although using HAS, the bonding between hydrated cement and sand in CF is weakened, there is still a need to break this bond by means of an extra force which is provided by ball milling in the current study.

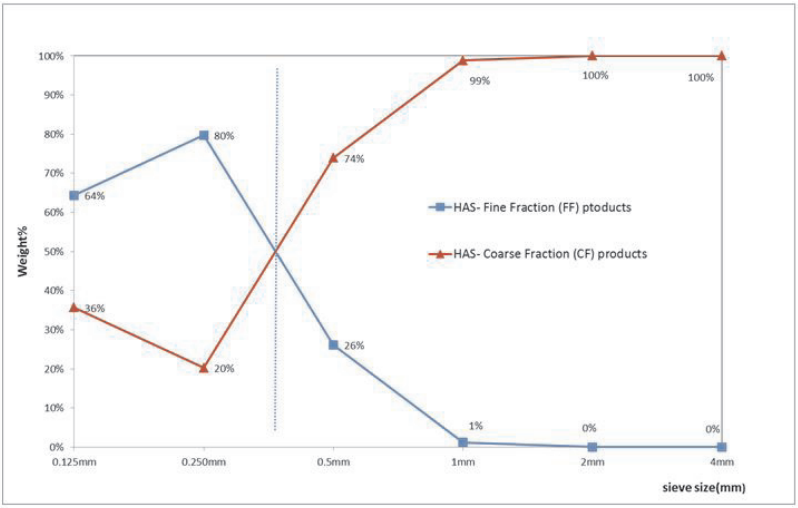

Figure 7-9: The recovery percentage of each size fraction into the two products of the HAS at 750°C.

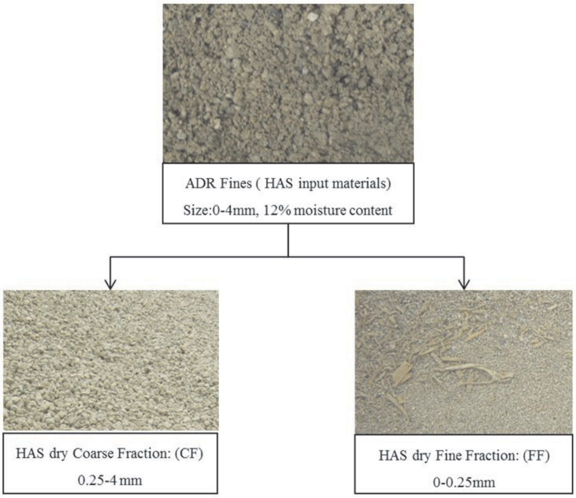

Figure 7-10: Input and outputs of HAS. 0-4mm ADR Fines is heated and separated to CF: 0.250-4mm and FF: 0-0.250mm. Depends on the temperature the wood is burnt or concentrated into FF.

7.4.2 Influence of milling versus heating

To evaluate the effect of heat treatment and ball milling, experimental results were analysed considering one variable (BM time or HAS temperature) at a time.

Figure 7-11 shows the cumulative size distribution of materials treated at different temperature by HAS and milled for 300 seconds. It is shown that the products size distributions moved towards the finer size range as the temperature increased. The same trend happens with increasing milling time at fixed heating temperature (for example at 750°C) (See Figure 7-12). As mentioned previously, one of the main aims of this study is to investigate the effect of heating and grinding on the production of 0-0.250mm fines which is mostly hardened cement rich. 2D contour and surface plot of weight percentage with respect of milling time and heating temperature in Figure 7-13 shows the positive influence of both parameters on increasing the mass of this fraction. Using the contour plot one can optimize the heating temperature and milling time for producing a specific amount of 0-0.250 mm fines at minimum cost. Ball Milling is usually a costly and an inefficient process in terms of energy requirements. Table 7-1 presents the costs of ball milling for both laboratory and industrial scale operations. The expected amount of CF for milling in an industrial scale is around 30 tons per hour (if ADR is run at 100 tons per hour). Changing the residence time from 300 to 90 seconds, while the throughput is constant at 30 tons per hour, demands a ball mill with a shorter length. Thus, the total cost of milling drops significantly.The experimental results in Figure 7-14 confirm that for production of a constant amount of fines (0-0.25 mm), the heating temperature can be increased to achieve reduced milling time accordingly. Decreasing the milling time is advantageous because less unwanted fine silica will be produced. This silica presents a health risk and it limits the hardened cement concentration.

In addition, according to Table 7-1, with reducing the residence time, the cost of milling reduces significantly. In addition to the cost, the quality of the products is another important factor to ensure an effective recycling process. For the quality aspects, we considered the removal of contaminants, grading of the products, density and water absorption of the produced sand and finally the amount of hardened cement concentrated in FF. Many organic substances such as wood are unstable in concrete when submitted to drying and wetting or freezing and thawing[18]. In order to enhance the quality of the recycled sand for high grade applications, wood and plastic must be removed. Experimental results based on Loss On Ignition (LOI) test show that this removal is complete at 500°C (see Figure 7-15). The LOI test consists of heating of some grams of each fraction at 950°C and allowing organic substances to escape until its mass stops changing. Figure 7-15 shows that the difference in LOI between materials recycled at 500°C and 750°C is small. It is therefore concluded that for the removal of organic materials, heating for 30 seconds at 500°C is sufficient. Amount of LOI has an inverse relation with the particle size. In general the amount of LOI increases with decreasing the particle size.

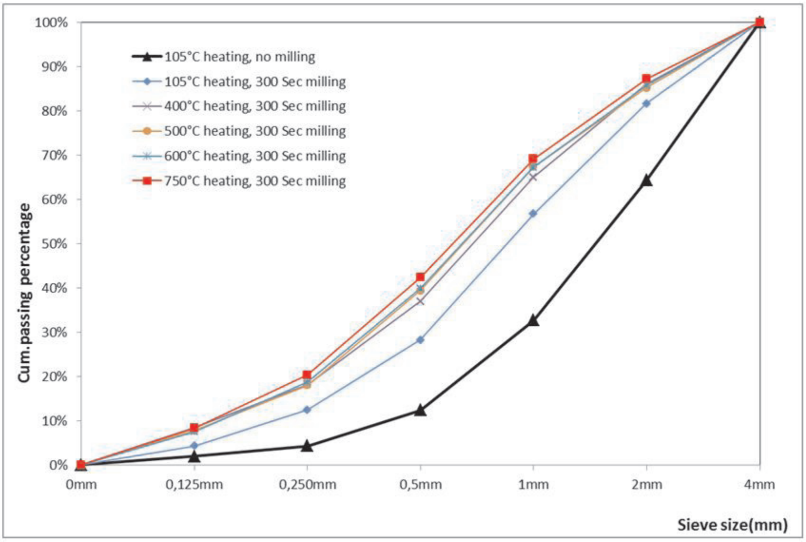

Figure 7-11: Particle size distribution of mill out-put while the milling time is constant at 300 second and mill input comes from different heating temperature in HAS.

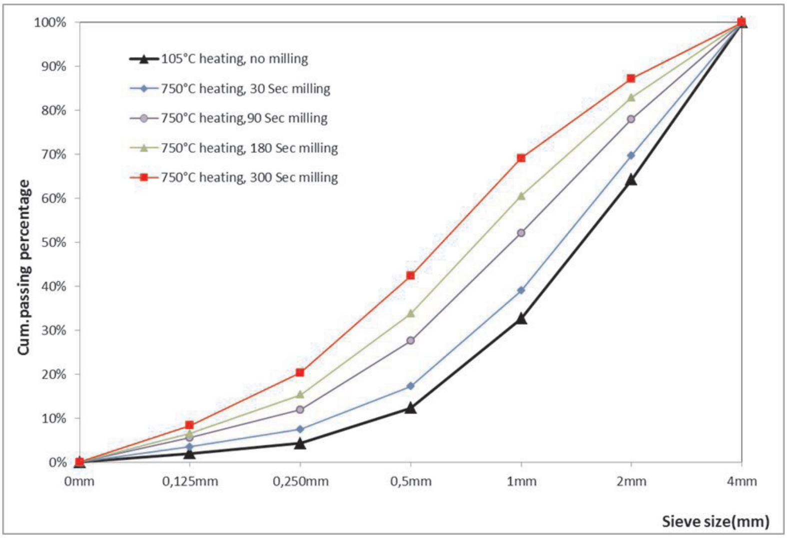

Figure 7-12: Particle size distribution of mill out-put while the milling time is variable and mill input come from constant heating temperature in HAS.

Table 7-1: The cost estimation for laboratory and industrial scale ball milling.

Ball mill condition														
Scale	residence time (seconds)	Capacity (kg/hour)	power (kW)	Energy cost (€/ton)	wear (€/ton)	Investment cost (€)	Capital cost in €/ton	diameter of ball mill (m)	length of ball mill (m)	Speed (rpm)	Speed (rph)	Weight of balls (N)	Height of drop (m)	Total cost (€/ton)
Laboratory	300	192	0.23	0.12	0.12	4294	4.97	0.6	0.3	45	2700	600	0.5	5.20
Industrial	300	30000	36.00	0.12	0.12	116281	0.84	1.2	3	22.5	1350	96000	1.0	1.08
Laboratory	90	640	0.23	0.04	0.04	4294	1.49	0.6	0.3	45	2700	600	0.5	1.56
Industrial	90	30000	10.80	0.04	0.04	53167	0.38	1.2	1	22.5	1350	28800	1.0	0.45

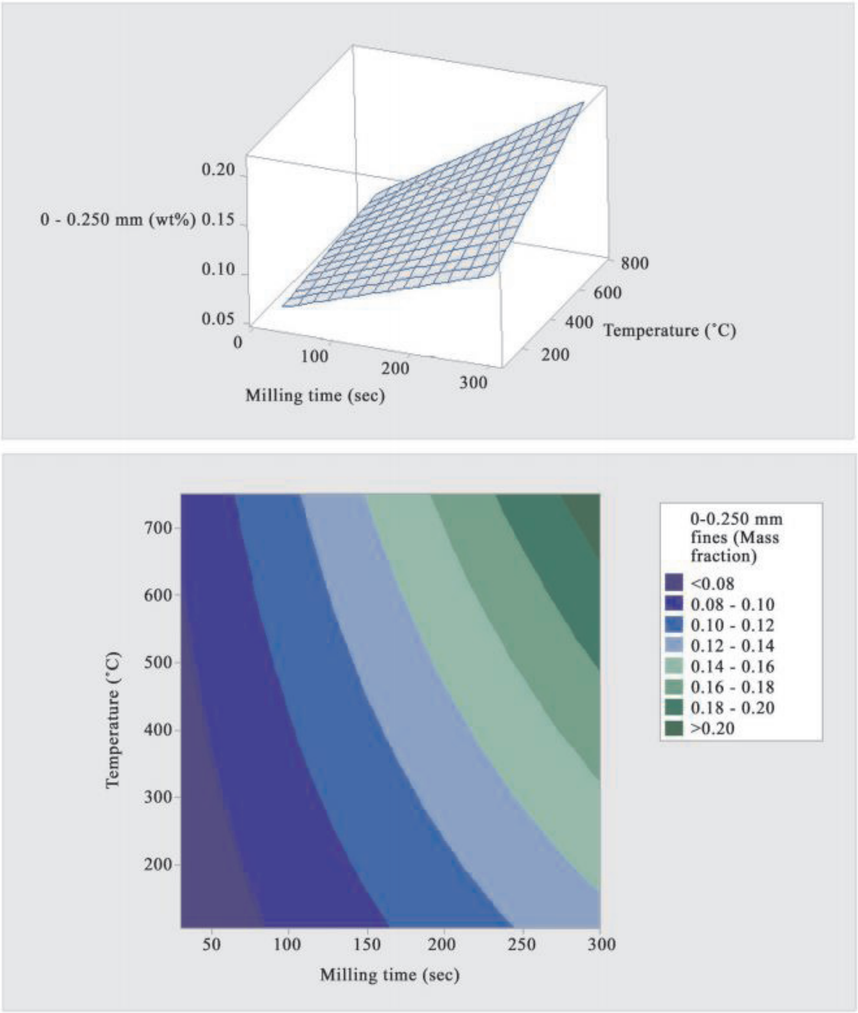

Figure 7-13: Surface and contour plot for 0-0.250 mm fines production while varying the temperature in HAS and timing in BM.

It indicates higher concentration of materials like wood in finer fractions. Another important quality aspect is the grading of the produced sand. Recycled sand should be well-graded and comply with the standards applied in the market. The grading limit for 0-4mm sand existing in the Dutch market (applied by Heidelberg cement) is illustrated in Figure 7-16 (Max and Min black lines). According to this figure, it is clear that the particle size distribution of the recycled sand heated to 500°C and milled for 90 seconds, is well within the limiting curves. Considering the current prices in the Dutch market, it is estimated that the selling price for the cementitious part (0-0.250mm) and sandy part (0.250-4 mm) would be at least 6 €/ton and 5 to

7.5 €/ton respectively. The original AF fractions, with limited applicability in the production of new building materials, have the value of ca 1€/ton.

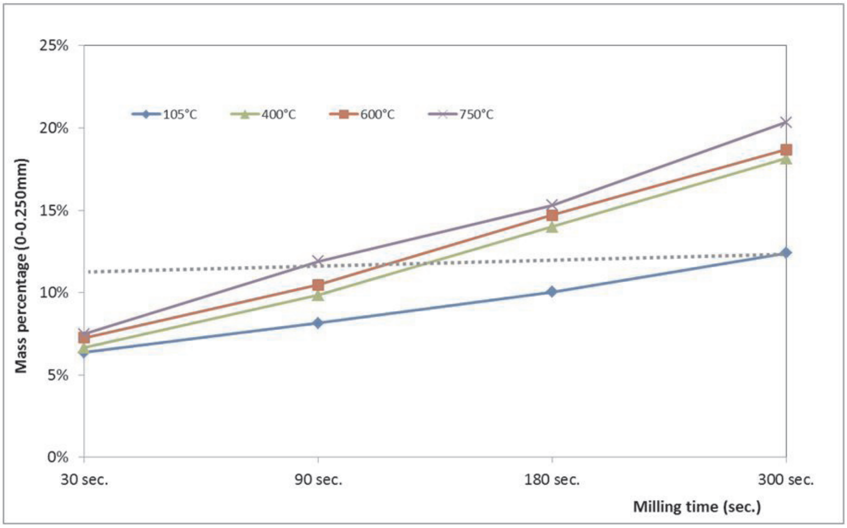

Figure 7-14: Reduction in the milling time by increasing the temperature for production the similar amount of 0-0.250mm.

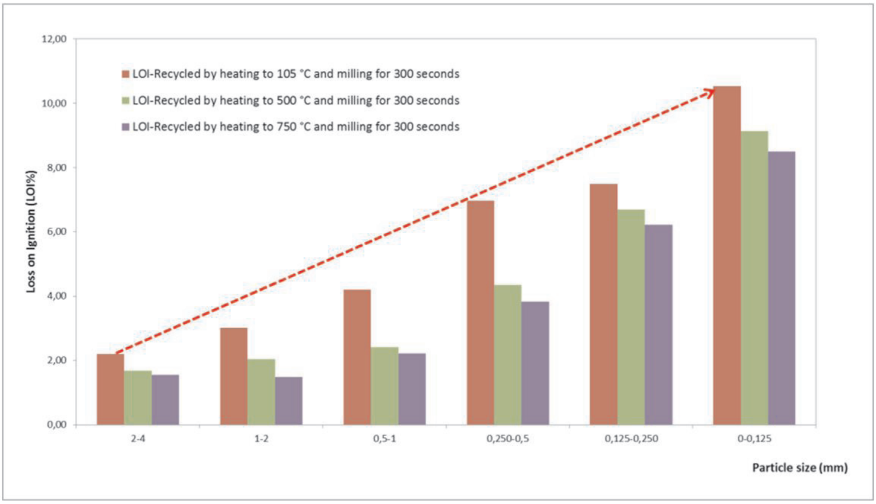

Figure 7-15: LOI of each fraction as an indication for their wood content.

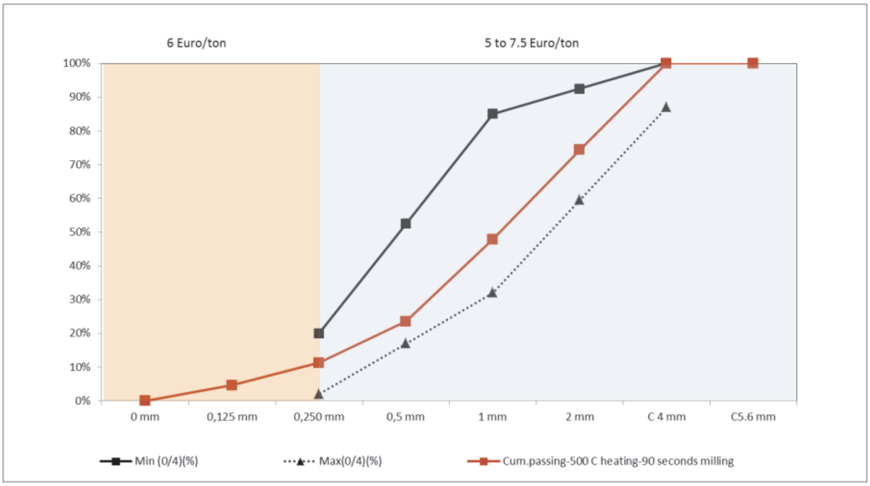

Figure 7-16: The grading requirements for 0-4mm sand (Max and Min lines) in the Dutch market compared to the grading of the recycled products.

Density and water absorption of aggregates are usually considered as being interrelated, showing an almost linear inverse relationship[2]. It is well-known that recycled aggregates or sand have lower density and consequently higher water absorption than the natural ones due to the attached hardened cement.

Figure 7-17 shows for example the density of each particle size resulting from 500°C and 300 seconds milling, measured using a gas pycnometer[19]. As it can be seen, particles smaller than 0.125 mm have a density of 2.24gr/cm^3, which is the lowest density among all the particle sizes. The densities have then a slightly increasing trend with particle size to 2.62 gr/cm^3 for 2-4mm particles. Previously Florea et al. [20], reported a lowest density of 2.45 gr/cm^3 for 0-0.63mm fraction and a density of 2.61 for 2-4mm recycled sand. Using a linear correlation equation between the density and water absorption of recycled aggregate expressed by de Juan et al. [21] the amount of water absorption is estimated and shown in Figure 7-18. Maximum water absorption for fine recycled aggregates is recommended to be in the range of 3%-13% in the most and least restrictive standards [2]. Water absorption shown in Figure 7-18 satisfies well the most restrictive standard of JIS A 5021. In the market, recycled sand with water absorption less than 5% is usually ranked in a good level of quality.

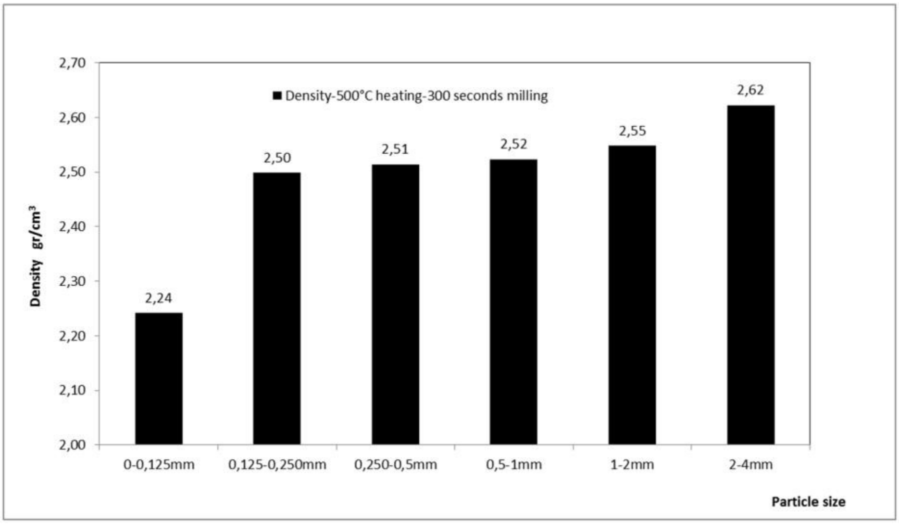

Figure 7-17: Densities of all fractions obtained from recycling process at 500°C and 300 seconds milling.

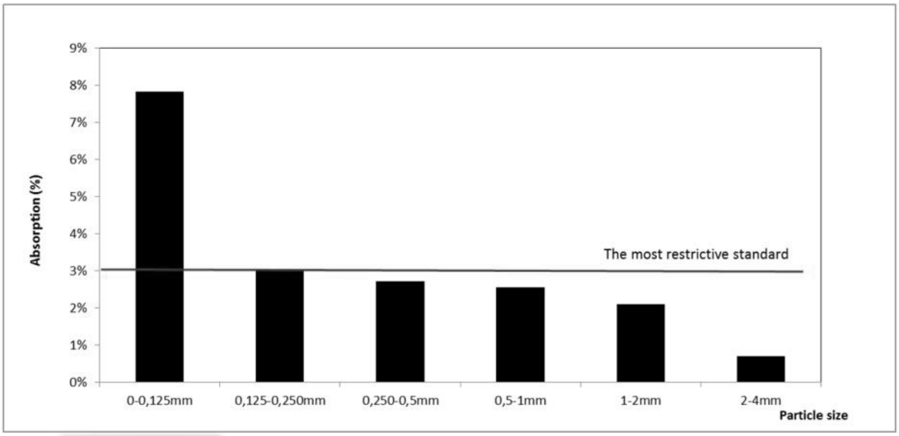

Figure 7-18: Estimated water absorption of all fractions obtained from a recycling process at 500°C with 300 seconds milling.

7.4.3 Properties of the recycled fractions

In general, crushed concrete fines contain mostly hardened cement and α-quartz (sand) originated from broken aggregates[20]. XRF analysis was carried out on various size fractions after the recycling procedures. The content of SiO_2 measured by

XRF ((SiO_2%)XRF) in fines is the sum of α-quartz (sand) and SiO_2 from the cement hydration products. The content of SiO_2 from hydration products can be traced back from the chemical composition of cement ((SiO_2%)CEM). Using DSC analysis, it is possible to calculate the amount of α-quartz in the recycled concrete aggregate fractions[19, 20]. The relationship between the parameters is expressed below[19]:

$$(SiO_2\%)XRF = (\alpha\text{-quartz}\%)DSC + (1-(\alpha\text{-quartz}\%)DSC).((SiO2\%)CEM) \qquad (1)$$

In the referred research it is reported that the error between XRF results and TG-DSC is relatively low (under 3%).

According to the evidence received from the demolished buildings in C2CA project, the type of cement in the utilised old concrete was CEMIII/B. Considering a typical chemical analysis of CEMIII/B received from ENCI, Netherlands, not taking into account possible slight changes in the composition of cement during the time, the amount of (SiO_2%)CEM was considered as 30%. Using the amount of (SiO_2%)XRF from the XRF analysis , it is possible to estimate the amount of hydrated cement and sand in various fractions.

Figure 7-19 (graphs A,B,C and D) shows the amount of hardened cement and sand in all considered fractions coming from various heating and milling processes. According to the figure, there are some differences observed between analysed materials. Firstly it is illustrated that the bigger particle sizes are cleaner than the small ones in terms of hardened cement content. Comparing the coarser fractions in all graphs in Figure 7-19, it is clear that the fractions 1-2mm and 2-4mm processed at 105°C and no milling (see graph A), contain the highest amount of attached hardened cement. The 2-4mm fraction in graph A contains 44% of hardened cement, while this number drops to 20% for the same particle size in graph D (processed at 750°C and 300 second milling). Considering the size 0-0.125mm in all graphs in Figure 7-19, the effect of the recycling process on concentration of hardened cement in this fraction is obvious. To understand the effect of the milling (independent from heating) on the hardened cement content of each fraction, graphs A and B in Figure 7-19 can be compared, and it is concluded that milling has an influence on the cleaning of the coarser fraction from hydrated cement and concentrating the cementitious powder into the finer fractions. By introducing the heat during the recycling, much cleaner sand (0.250-4mm) is produced. Increasing the heating temperature to 750°C may cause the sandy part to get more brittle and results in an increment of the sand percentage in very fine fractions (graph D).

Figure 7-20 presents the cumulative distribution of hardened cement and sand based on the particle size distribution of the final output materials from the recycling process and hardened cement-sand content of each size fraction. According to the Figure 7-20 graph A (processed at 105°C and no milling) just 6% recovery of the total hydrated cement (existing in 0-4mm fraction) can be achieved for particles under 0.250mm. By adding the milling step (see graph B- Figure 7-20) the recovery raises to 19% for the particles smaller than 0.250 mm size. With heating at 500°C and 750°C, the amount of cement recovery in particles under 0.250 mm raises to 34% and 39%, respectively. Considering Figure 7-20 graph D (750°C heating and 300 sec milling), the cumulative recovery of hardened cement for fractions below 1 mm is 82%, while this number drops to 32% for dry materials processed at 105°C and no milling (graph A). When comparing different graphs of Figure 7-20, in terms of the efficiency of recovering of hardened cement, it can be noticed that there is a slight difference between the percentage of the produced 0-0.250mm at 500°C and 750°C. Therefore, it seems more advantageous to keep the recycling temperature at 500°C. Table 7-2 shows a comparison among the chemical composition of ADR fines and some raw meal materials such as clay and limestone (in two different quality levels). In the same table, the chemical composition of the 0-0.125mm produced within this study is added as well. A comparison between the numbers shows that the amounts of CaO, Al_2O_3 and Fe_2O_3 in the produced 0-0.125mm fraction are well comparable with the amounts in low-quality limestone (around 35 wt.% CaO).

The required heat energy for drying of one ton ADR fines is estimated to be 300 MJ. Based on the Ecoinvent database, 0.0716 kg CO_2 will be produced for the production of 1 MJ heat (if the fuel is gas)[22]. Therefore, the amount of CO_2 emission resulted from heating of ADR fines for the production of 1 ton of hardened cement is estimated to be 108kg. On the other hand, the clinker emission factor is the product of the fraction of lime in the clinker multiplied by the ratio of the mass of CO_2 released per unit of lime[23]. Thus, for the production of one ton of clinker, almost 344 kg of chemical CO_2 will be released. A comparison between the aforesaid numbers shows that by reusing the cement paste from old concrete the release of the chemically bound CO_2 will be reduced by a factor of three.

Table 7-2: XRF values for ADR fines and FF in comparison to limestone and clay component (Mass%).

Oxides	ADR fines directly used in C2CA trial	FF (0-0.125 mm) resulted from heating and grinding	Example Clay	65% $CaCO_3$ (marl) Limestone-low quality	95% $CaCO_3$ Limestone-high quality
SiO_2	75.49	41.2	67.30	21.80	2.83
Al_2O_3	4.57	6.42	9.00	5.48	0.69
TiO_2	0.23	0.41	-	0.26	0.03
MnO	0.13	0.13	-	0.03	0.03
Fe_2O_3	1.64	2.97	4.30	1.86	0.28
CaO	11.24	35.16	7.30	36.60	53.00
MgO	1.23	1.79	2.00	0.87	0.61
K_2O	0.85	0.78	1.20	0.97	0.13
Na_2O	0.43	-	1.40	0.13	0.04
SO_3	0.78	1.75	0.30	0.56	0.04
P_2O_5	0.07	-	-	0.08	0.06
LOI	9.03	9.13	7.20	30.88	41.90

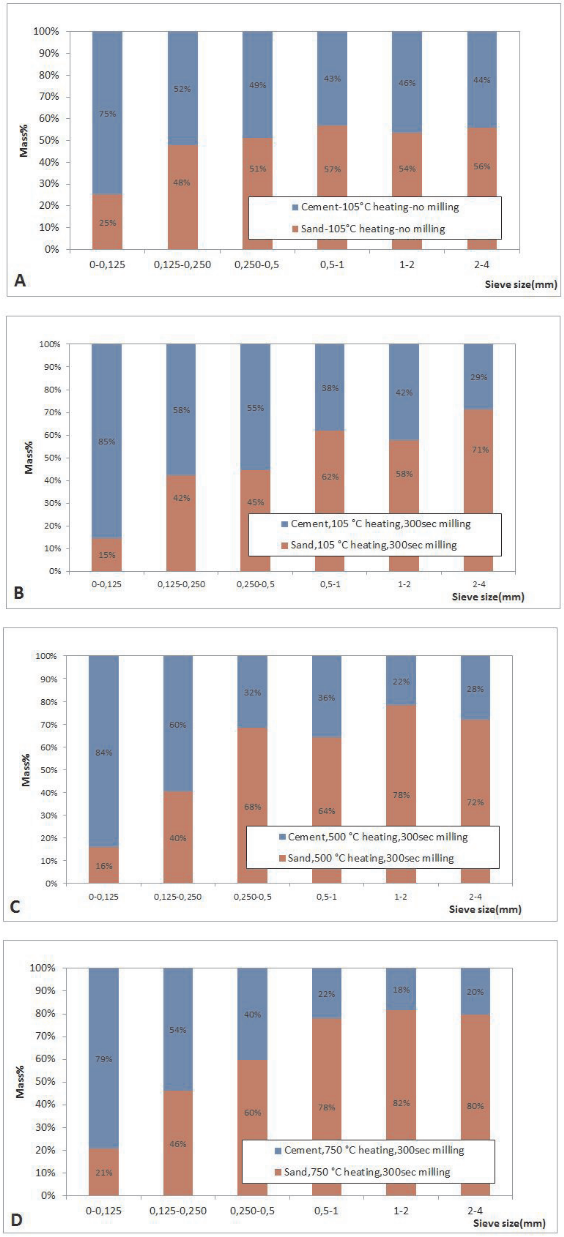

Figure 7-19: Composition of all recycled fractions divided into sand and hardened cement components for various recycling conditions.

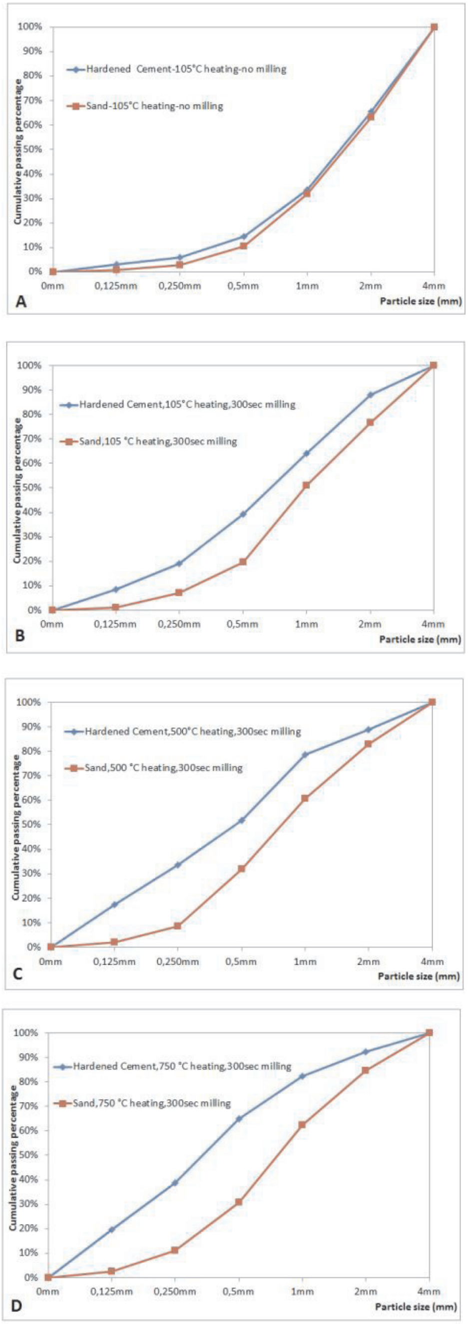

Figure 7-20: Cumulative distribution of the hardened cement paste and sand for various recycling conditions.

7.5 CONCLUSION

While at present crushed concrete fines accounts for a massive by-product of concrete recycling, construction industry has a limited tendency to use this material in new applications. On the other hand, the significant importance of preserving natural resources, reduction of CO_2 emissions and considering crushed concrete fines as a valuable resource and not as a waste, are the main driving forces to develop a proper technology for recycling of crushed concrete fines into valuable products like hardened cement and clean sand. The C2CA process has been able to produce high quality recycled aggregates for structural applications. However, in order to close the C2CA concrete recycling loop, there is a need for recycling and upgrading of the fines that is almost 40wt.% of the whole EOL crushed concrete. Solving the problems with crushed concrete fines is strongly associated with the removal of very small particles (0-0.250mm) and contaminants. Considering the wet and sticky state of the crushed concrete fines, a heating step in the recycling process seems inevitable to make the process robust.

Laboratory experiments were carried out to investigate the influence of different levels of heating and grinding on the hardened cement and sand recovery from moisturized and contaminated crushed concrete fines. A lab scale Heating-Air classification system (HAS) was designed and constructed. A combination of heat and air classification in HAS, resulted in a proper separation of finer (0-0.250mm) from coarser fractions while it simultaneously weakened the cementitious bonding in the materials.

Grinding of the coarser output of HAS in a ball mill enhanced the liberation of the hardened cement. Experimental results show that heating of the materials to 500 °C for a duration of 30 seconds, results in a significantly reduced milling time. This is important for the milling cost and to avoid the production of new fine silica during the grinding. When comparing different heating temperatures in terms of the efficiency, recovery of hardened cement, sand and contaminants removal, 500°C is concluded as the most suitable temperature. The quality of materials from the proposed recycling process complies with market demands and existing standards. The density and water absorption of the produced sand satisfies well the most restrictive standards. Moreover, the experimental results show that the removal of contaminants is complete by heating of the materials to 500 °C. The difference in cement recovery in the very fine fraction after heating to 500 °C and 750 °C is small. This is another reason for keeping the heating temperature to around 500 °C.

The fraction 0-0.125 mm always shows the highest percentage of the CaO and consequently hardened cement. The amount of CaO in the produced very fine fraction is comparable with the amount of CaO in low-quality limestone. Changing the recycling variables, results in different recovery percentage of hardened cement in finer fraction. Based on the required chemical composition from the cement production industries, it is possible to cut the size of the hardened cement rich part on 0-0.250mm or 0-0.125mm.

By reusing the hardened cement from old concrete the release of the chemically bound CO_2 will be reduced by a factor of three. On the basis of the encouraging results obtained and proven principles, a pilot scale set-up will be developed for high volume recycling of crushed concrete fines.

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Summary & Follow-up research

Summary

Around 540 million tons of Construction and Demolition Waste (CDW) are yearly generated in Europe. Recent studies on the characterization of a range of CDW samples at European level revealed that the predominant material constituent is concrete, varying in the range of 60 to 70 wt.% of CDW. Currently, road foundation is the main outlet for using crushed end of life concrete in the Netherlands. However, it is foreseen that by 2025 the amount of available end of life concrete will have risen dramatically. This is because from one side the demand for road foundation will decline and from the other side a lot of buildings that were built after the second world war are closing to their end of life.

Despite the urgency of creating a sustainable solution for concrete waste, there has not been a large driving force for recycling it into prime grade materials. This low motivation has a root in existing cultural, environmental, political and economic constraints. For concrete to concrete recycling most of the time a lack of economic benefits puts obstacles for the technology and the business model. This indicates that currently the market for recycled concrete may not be large enough and needs innovations to create more attractive products. The C2CA concrete to concrete recycling concept delivers such innovations.

The C2CA process aims at a cost-effective system approach to recycle end of life concrete to hardened cement and clean aggregates. It applies a number of innovative technologies to make the products of the concrete recycling plant suitable as input materials for cement and mortar or pre-cast concrete industries. The technologies considered are smart demolition to produce crushed concrete with low levels of contaminants, followed by mechanical upgrading of the material on-site into an aggregate product with sensor-based on-line quality assurance and a cement-paste concentrate that can be processed (off-site) into a low-CO_2 input material for new cement. After crushing and sorting out big contaminants, liberation of the cement paste is promoted by several minutes of grinding in an autogenous mill. A new low-cost classification technology, called Advanced Dry Recovery (ADR) is then applied to remove the fines and light contaminants and produce a clean aggregate with online quality control. By now, these technologies have been demonstrated at industrial conditions. HAS technology, presently developed to laboratory level, should then be applied to further recycle ADR fines into streams of hardened cement and clean sand. This PhD project investigated and developed the C2CA concrete recycling process for recycling EOL concrete to both recycled aggregates, with a quality equivalent to natural aggregates and suitable for use in new mortar and pre-fab elements, and a hardened cement rich stream for low- CO_2 cement production and other binder products. The economics of the process is attractive because of the low energy demand and high volume capacities of the applied unit operations, the possibility of in-situ processing (no need for materials transportation), and the very small amount of residue (virtually eliminating the cost of land-filling). In order to develop and fine-tune the C2CA separation process some objectives had to be set:

- Studying the ADR performance with the aim of creating highly concentrated flows of clean recycled aggregate and ADR fines.
- Understanding the mechanisms inside of an autogenous mill and the effect of shear-compression forces on the hardened cement recovery.
- Investigation on the effect of C2CA input variables (milling intensity, ADR cut-size point, parent concrete properties and the recipe of the new concrete) on the output quality (the visible quality of recycled aggregates, the workability, development of strength and durability of the recycled aggregate concrete).
- Developing an efficient process for separation of hardened cement and clean sand from ADR fines

The above objectives have been met through experiments, simulation, laboratory tests, performance assessments and experiments in collaboration with industry at small and big scale. Below the summary of the research is given, followed by an overview on future activities in follow-up projects:

Chapter 2 presents results from the first demonstration of the C2CA process. Lab-scale application of the C2CA process was conducted on a sample of circa 40 tonnes of end of life concrete coming from smart dismantling and demolition of two governmental towers in Groningen. Experimental results showed that ADR performs efficiently to separate the fine fraction, which is mostly associated with high moisture content including wood and other floating materials. The produced clean Recycled Aggregate (RA) was tested into Recycled Aggregate Concrete (RAC) in collaboration with AGH, to investigate the workability, compressive strength and durability compared to concrete made from natural aggregate. The main outcome of this experiment is that by using the recipe developed by AGH, it is possible to obtain recycled aggregate concrete with a higher compressive strength (at early ages) compared to concrete made of natural aggregates (NAC), while the same amount of cement is used in both types of concrete. Although the science behind this success is not yet fully clarified, it is clear that fine materials (-2 mm) have to be removed from the crushed concrete and fragile cement paste has to be removed from the surface of aggregate. AGH found that, in order to reach this good result, it is important to establish the right water/cement ratio in the interfacial transition zone between recycled aggregate and new cement. Too high amount of water creates pores and too low amount of water stops the hydration process. Thus, making RAC based on a modified recipe tuned to the RA is a key step. AGH applied a consistency test to determine the correct amount of water. In the industry, aggregates are usually saturated with water due to exposure to rain and snow, which increases uncertainty over the actual moisture content of aggregates. Thus, the moisture content of recycled aggreates should be controlled carefully and mix designs should be adapted. Industries that have no insight or suitable recipes for using recycled aggregates should not produce mortar from this resource. The results for the freeze-thaw resistance showed that the recycled concrete performed less well than NAC but still fulfilled the strict requirements of the Polish standard.

In the course of the second demonstration case of the C2CA technology, recycled aggregate was tested into RAC by Holcim and Heidelbergcement to evaluate the influence of RA substitution, water/cement ratio and type of cement on the mechanical and durability performance of the RAC in an industrial trial. It is striking that in this industrial trial, RAC samples did not show the high early compressive strength that was observed in the first trial. According to the results, using RA as alternative aggregate in concrete might increase the overall porosity of concrete compared to the reference concrete. Besides, it was shown that applying higher water/cement ratios by increasing the effective mixing water induces more porosity to the system. As it is observed in the experimental results in Chapter 3, concrete samples with the higher amount of mixing water and lower amount of strength show in most cases worse mechanical and durability properties. It is clear that adverse effects of RA escalate applying a higher water/cement ratio in the system. However, also according to the results, modifying the concrete mix design, based on lower water to cement ratio and using superplasticizer, results in better mechanical and durability properties in RAC. The mechanical and chemical properties of the cement paste are directly responsible for higher resistance of concrete under exposure to aggressive conditions. Thus, all durability properties can be influenced by the choice of cement and the amount of mixing water and superplasticizer in the concrete mixture. Based on the C2CA concrete test program and the current situation in European standards and regulations it is concluded that RA is a suitable alternative to natural coarse aggregates for a significant share of concrete applications including structural applications. Replacing more than 50% of the natural coarse aggregate with recycled aggregate- which corresponds to using more than 500 kg of RA per m3 of new concrete needs to be done more carefully and applications should be limited to mild exposure conditions.

In the C2CA concrete recycling process, autogenous milling of crushed end of life concrete is used to increase the liberation of the cement paste. Chapter 4 presents the research carried out to understand how shear and compression, and the combined effect of them inside of an autogenous mill, influence the cement recovery into the fine fraction. In order to simulate forces in an autogenous mill in a controlled way, a new set-up (SCM) was constructed. A central composite experimental design with the help of the MINITAB 16 software for predicting the conditions of 13 experimental runs was used. According to the regression analysis, the effect of shear and compression on the cement recovery for both 0-1 mm and 0-0.5 mm fractions was found to be strongly linear ($P< 0.001$). Comparing the main effect plots, force (compression) is found to be slightly more effective than duration (shear). However, based on the achieved results, it is possible to replace the shear and compression with each other with the purpose of raising the cement recovery. Therefore, high amount of low-cost shear in an autogenous mill will eliminate the need for the expensive pure compression in a crusher. Variation in the strength of concrete could be compensated by simple changes in the mill feeding, the residence time and the bed height.

An investigation on the relation between the C2CA input variables and output quality is given in Chapter 5. The main factors in the C2CA process which may influence the properties of RA or RAC include the type of Parent Concrete (PC), the intensity of autogenous milling (changing the amount of shear and compression inside of a mill) and the ADR cut-size point (usage of +2mm or +4mm RA in the new concrete). To conduct the study, first of all, three types of concrete with a high demand in the Dutch market were cast as PC and their fresh and hardened properties were tested. After near one year curing, PC samples were recycled independently varying the type of PC and intensity of autogenous milling. Experimental variables resulted in the production of eight types of RA. The physical, mechanical and durability properties of the produced RA were tested and the effect of experimental variables on these properties were investigated. According to the results, the type of PC is the prevailing parameter for the final properties of RA, in comparison with the milling intensity. Moreover, it is observed that variation in the milling intensity mostly influences the properties of RA produced from a lower strength PC. Experiments followed that studied the performance of the RA in the new concrete. Four types of RAC were produced based on the modified recipe of their corresponding PCs (similar to the route mentioned in Chapter 2). For the modification of the recipes, water absorption and density of RA were taken into account while the amount of applied cement and consistency class was kept similar to the corresponding PC. Experimental results show that the compressive strengths of all produced RAC samples were higher than PC, especially at early ages. This confirmed the spectacular potential of using RA. Taking advantage of today's demand for fast track work in the construction industry and for saving time for the production of prefab elements, the aforesaid unique property of RAC would be key to improve the social awareness towards application of this valuable material. Good performance of RAC with the incorporation of 2-4mm ADR fines and RA, confirms the possibility of setting ADR cut-size point to 2 mm.

Results of the first case study of the C2CA project showed that the wood content of 4-16 mm recycled aggregates is well within the strictest limit of the EU standard. However, there are still large visible pieces of wood and plastic in the +16 mm RA fraction, which concentration, albeit within the standards, does not satisfy the users. In order to solve this problem the feasibility of applying two existing technologies (near infrared sensor sorting and wind sifting) to remove contaminants is studied in Chapter 6. In addition, an overview on the effect of autogenous milling on the size of contaminants is given in this chapter. Results show that industrial autogenous milling reduces the mass percentage of contaminants bigger than 5mm by 30% and shift them to the fine fraction. There is a clear effect of milling on the size reduction of brick. A similar trend can be seen for wood contaminants but in a less outstanding way. It is revealed that the combination of two technologies (NIR sensor sorting and wind sifting) will remove most of the contaminants from +16 mm RA.

The C2CA process has been able to produce high quality recycled aggregates for structural applications. However, in order to close the C2CA concrete recycling loop, there is a need for recycling and upgrading of the fines that is almost 40wt.% of the whole EOL crushed concrete flow. Solving the problems with crushed concrete fines is strongly associated with the removal of very small particles (0-0.250mm) and contaminants. Considering the wet and sticky state of the crushed concrete fines, a heating step in the recycling process seems inevitable to make the process robust.

Laboratory experiments were carried out to investigate the influence of different levels of heating and grinding on the hardened cement and sand recovery from moisturized and contaminated crushed concrete fines. A lab scale Heating-Air classification System (HAS) was designed and constructed. The combination of heat and air classification in HAS resulted in a proper separation of finer (0-0.250mm) from coarser fractions while it simultaneously weakened the cementitious bonding in the materials.

Grinding of the coarser output of HAS in a ball mill enhanced the liberation of the hardened cement. Experimental results show that heating of the materials to 500°C for a duration of 30 seconds results in a significantly reduced milling time. This is important for the milling cost and to avoid the production of new fine silica during grinding. When comparing different heating temperatures in terms of the efficiency, recovery of hardened cement, sand and contaminants removal, 500°C is concluded as the most suitable temperature. The quality of materials from the proposed HAS process complies with market demands and existing standards. The density and water absorption of the produced sand satisfies well the most restrictive standards. Moreover, the experimental results show that the removal of contaminants is complete by heating of the materials to 500°C. The difference in cement recovery in the very fine fraction after heating to 500°C and 750°C is small. This is another reason for keeping the heating temperature to around 500°C. The fraction 0-0.125 mm always shows the highest percentage of the CaO and consequently of hardened cement. The amount of CaO in the produced very fine fraction is comparable with the amount of CaO in low-quality limestone, so that this flow can in fact be a low CO_2 substitution for limestone. Based on the required chemical composition from the cement production industries, it is possible to cut the size of the hardened cement rich part on 0-0.250mm or 0-0.125mm.

By reusing the hardened cement produced by HAS the release of the chemically bound CO_2 will be reduced by a factor of three. On the basis of the encouraging results obtained and proven principles, a pilot scale set-up will be developed for high volume recycling of crushed concrete fines in the EU project VEEP.

Follow-up research

While this thesis mainly focused on the production of upgraded coarse recycled aggregate, at the end some proof of concept at TRL3 was also performed separating the hardened cement paste and contaminants from fine recycled sand. This proof of concept constitutes the starting point for the new HAS technology proposed in the Horizon 2020 VEEP project, aiming to shift the technology readiness level from TRL3 to TRL5/6. In addition, the novel HAS is expected to produce upgraded recycled sands and supplementary cementitious materials for new concrete production. The ADR technology will be also adapted to light-weight concrete waste recycling and the combination of ADR and HAS technology for simultaneous production of coarse and fine recycled aggregates will be an innovative solution in VEEP.

At present, according to rough estimates, less than 5% of recycled concrete aggregates are used in new concrete manufacturing. Nevertheless, replacement levels are typically allowed up to 20% or 30% of the coarse fraction of the recycled natural weight concrete aggregate, with acceptable negative effects on visual quality, workability, compressive strength and durability of the mortar and concrete. This thesis revealed that the use of the ADR technology can lead to higher quality coarse recycled concrete aggregates for their use in concrete, on the basis that moisture absorbing fine fractions and contaminants are effectively removed from the coarse fractions. That fact can even lead to superior compressive strength that opens up new opportunities for the construction industry. The resulting concrete hardens much faster than concrete made from natural aggregate, while the same amount of cement is being used. It might allow the prefab industry to reduce the use of additional cement or additives and to increase the productivity of the existing facilities. The use of fine recycled concrete fractions in new concrete production is still restricted due to high water absorption, low density and the presence of impurities. As aforementioned, the novel HAS technology demonstrated that recycled sands (with absorption values below 3% and without organic fractions) and a potential cementitious powder below 0.25 mm can be produced. The effect of those recycled fractions in cement based materials and new concrete has to be yet studied.

Samenvatting

Rond de 540 miljoen ton Bouw- en Sloop Afval (BSA) wordt jaarlijks geproduceerd in Europa. In recente studies bleek uit karakterisering van diverse CDW monsters op Europees niveau dat beton het overheersende bestanddeel is, variërend van 60 tot 70 gew.% van BSA. Op dit moment is wegfundering de belangrijkste afzetmarkt voor gebroken einde-levensduur beton in Nederland. Echter, de voorspelling is dat in 2025 de hoeveelheid beschikbare betonafval drastisch zal zijn gestegen. De reden is dat aan de ene kant de vraag naar wegfundering zal afnemen en aan de andere kant veel gebouwen van na de tweede wereldoorlog aan het einde van hun levensduur komen.

Ondanks de urgentie van het creëren van een duurzame oplossing voor betonafval, is er tot nu toe geen grote drijvende kracht geweest voor het recyclen van dit materiaal op een hoogwaardige manier. Dit gebrek aan motivatie komt voort uit bestaande culturele, ecologische, politieke en economische randvoorwaarden. Meestal levert de afwezigheid van economische voordelen van beton naar beton recycling obstakels op voor de technologie en het business model . Dit geeft aan dat op dit moment de markt voor gerecycled beton niet groot genoeg is en er innovaties nodig zijn om meer aantrekkelijke producten te creëren. Het C2CA beton recycling concept draagt dergelijke innovaties aan.

Het C2CA proces is een kosteneffectieve systeembenadering voor het recyclen van betonafval naar uitgehard cement en schoon zand en grind. Het omvat een aantal innovatieve technologieën die de producten van de beton recycling geschikt maken als grondstoffen voor cement en mortel, en voor de betonwaren industrie. De betreffende technologieën zijn: slim slopen om betonstromen met lage niveaus van verontreinigingen te verkrijgen, locale mechanische opwerking van het materiaal tot een grind product met on-line kwaliteitsborging door sensortechnologie en een cement-pasta concentraat dat (elders) kan worden verwerkt tot een materiaal voor nieuw cement met een lage CO_2-uitstoot. Na het breken en het verwijderen van grote verontreinigingen , wordt het vrijkomen van de cementpasta uit het materiaal bevorderd door een aantal minuten malen in een autogene molen. Een nieuwe kosten-effectieve classificatie technologie, genaamd Advanced Dry Recovery (ADR) wordt vervolgens toegepast om fijne fracties en lichte verontreinigingen af te scheiden en grind te produceren met een sensor-gestuurde kwaliteit. Deze technologieen zijn ondertussen op industriele schaal gedemonstreerd. HAS-technologie, op dit moment nog een laboratoriumtechniek, moet vervolgens de fijne fracties uit de ADR omzetten in stromen van gehard cement en schoon zand.

Dit promotieonderzoek onderzocht en ontwikkelde het C2CA recyclingproces dat beton in de einde levensduur fase recyclet naar zand en grind van gelijke kwaliteit als natuurlijke aggregaat, geschikt voor het gebruik in nieuwe mortel en pre-fab elemen-

ten, en naar een gehard cement concentraat voor de productie van laag CO_2 cement en andere binders.
De economie van het proces is aantrekkelijk vanwege de lage energiebehoefte en hoge doorzet van de toegepaste verwerkingsstappen, de mogelijkheid om in-situ verwerking (geen materiaaltransport), en de zeer kleine hoeveelheid residu (vrijwel het elimineren van stortkosten). De ontwikkeling en het verfijnen van het C2CA scheidingsproces richtten zich op een aantal doelstellingen:

- Het bestuderen van het ADR proces met als doel het creëren van zeer geconcentreerde stromen van schoon gerecycled aggregaat en fijne fractie..
- Het begrijpen van de mechanismen in een autogeen molen en van het effect van shear compressie krachten op de terugwinning van het geharde cement.
- Onderzoek naar het effect van C2CA input variabelen (maalintensiteit, het scheidingspunt van de ADR, de eigenschappen van het einde levensduur beton en het recept van het nieuwe beton) op de kwaliteit van de producten (de zichtbare kwaliteit van gerecycled zand en grind, de verwerkbaarheid, de ontwikkeling van sterkte en duurzaamheid van het gerecyclede beton).
- Het ontwikkelen van een efficiënt proces voor het scheiden van gehard cement en schoon zand uit de fijne fractie van de ADR.

De bovenstaande doelstellingen zijn verwezenlijkt door middel van experimenten, simulatie, laboratoriumtesten, veldtesten en experimenten op kleine en grote schaal in samenwerking met de industrie. Hieronder wordt dat onderzoek samengevat, gevolgd door een overzicht van toekomstige activiteiten in volgprojecten:
In hoofdstuk 2 worden de resultaten van de eerste demonstratie van het C2CA proces gepresenteerd. Het C2CA proces werd uitgevoerd in het laboratorium op een steekproef van circa 40 ton van afgedankt beton afkomstig van slimme ontmanteling en sloop van twee overheidsgebouwen in Groningen. De resultaten toonden aan dat de ADR de fijne fractie, die een hoog vochtgehalte en hout en andere drijvende materialen bevat, efficiënt afscheidt. Het geproduceerde schone Recycle-Grind (RG) werd getest in Recycle-Grind-Beton (RGB) in samenwerking met AGH, om de verwerkbaarheid, druksterkte en duurzaamheid te onderzoeken ten opzichte van beton gemaakt van natuurlijke aggregaat. Het belangrijkste resultaat van dit experiment is dat met het recept van AGH het mogelijk is om recycle-beton te produceren met een hogere druksterkte (bij korte uithardingstijd) in vergelijking met beton gemaakt van natuurlijk aggregaat (NGB), met dezelfde hoeveelheid cement in beide soorten beton. Hoewel de wetenschap achter dit succes nog niet volledig is achterhaald, is het duidelijk dat fijn materiaal (-2 mm) in het gebroken beton en de breekbare cementpasta aan het oppervlak van het grind moet worden verwijderd. AGH heeft vastgesteld dat het voor een goed resultaat belangrijk is om de juiste wa-

ter/cement verhouding in de overgangszone tussen gerecycled aggregaat en nieuwe cement te realiseren.Teveel water creëert poriën en een te lage hoeveelheid water stopt het hydratatie proces. Bij het maken van RGB is een aangepast recept dus een belangrijk onderdeel. AGH past een consistentie test toe om de juiste hoeveelheid water te bepalen. In de industrie worden zand en grind vaak verzadigd met water door blootstelling aan regen en sneeuw, waardoor de onzekerheid over het feitelijke vochtgehalte toeneemt.Daarom moet het vochtgehalte van gerecycled granulaat zorgvuldig worden gecontroleerd en het meng ontwerp moet worden aangepast. Industrieën die geen inzicht in of geschikte recepten voor het gebruik van gerecycled zand en grind hebben kunnen beter geen mortel met deze materialen produceren. De resultaten voor de vries-dooi weerstand lieten zien dat gerecycled beton minder goed presteert dan NGB maar voldoet aan de strenge eisen van de Poolse standaard.

In de tweede demonstratie van de C2CA technologie werd gerecycled aggregaat door Holcim en Heidelbergcement getest in RAC om de invloed van het percentage RG substitutie, de water/cement-verhouding en het soort cement op de mechanische en duurzaamheid prestaties van de RGB te evalueren. Het is opvallend dat in deze industriële testen de RGB monsters niet de hoge vroege druksterkte gaven zoals in de eerste proef werd waargenomen.

Volgens de resultaten zou gebruik van RG als alternatief aggregaat in beton de totale porositeit van beton in vergelijking met het referentie beton kunnen verhogen. Daarnaast bleek dat een hogere water/cement ratio, door de hoeveelheid mengwater te verhogen nog meer porositeit induceert. Zoals waargenomen in de experimentele resultaten van hoofdstuk 3, laten beton proefstukken met de grootste hoeveelheid mengwater en lagere sterkte in de meeste gevallen slechtere mechanische eigenschappen en duurzaamheid zien. Het is duidelijk dat nadelige eigenschappen van RA zijn geëscaleerd door het aanbrengen van een grotere water/cement ratio in het systeem. Echter, volgens de zelfde resultaten, leidt aanpassing van het betonmengsel ontwerp, gebaseerd op een lagere water/cement verhouding en het gebruik van superplastificeerder, tot betere mechanische eigenschappen en duurzaamheid in RGB. De mechanische en chemische eigenschappen van de cementpasta zijn rechtstreeks verantwoordelijk voor de hogere weerstand van het beton onder blootstelling aan agressieve omstandigheden. Zo kunnen alle duurzame eigenschappen worden beïnvloed door de keuze van cement en de hoeveelheid mengwater en superplastificeerder in het betonmengsel. Op basis van het C2CA testprogramma en de huidige Europese normen en voorschriften wordt geconcludeerd dat RG een geschikt alternatief is voor natuurlijk grind voor een aanzienlijk deel van de beton toepassingen, waaronder structurele toepassingen. Het vervangen van meer dan 50% van grof natuurlijk aggregaat door gerecycled aggregaat, dat wil zeggen het gebruik van meer dan 500 kg RG per m3 van het nieuwe beton vereist meer zorg en toepassingen moeten worden beperkt tot milde condities.

In het C2CA beton recycling proces wordt autogeen malen van gebroken oud beton gebruikt om de losmaking van cementpasta te verhogen. Hoofdstuk 4 presenteert het onderzoek uitgevoerd om te begrijpen hoe afschuiving en compressie, en hun gecombineerde effect in een autogene molen, van invloed is op de terugwinning van cement in de fijne fractie. Om op een gecontroleerde manier de krachten te simuleren in een autogene molen is een nieuwe set-up (SCM) geconstrueerd. Een proefopzet met behulp van de MINITAB 16 software is gebruikt om de condities van 13 experimenten op te stellen. Via regressieanalyse bleek het effect van afschuiving en compressie op de terugwinning van cement voor zowel de 0-1 mm en de 0-0,5 mm fracties sterk lineair (P <0,001). In vergelijking is de kracht (compressie) iets effectiever dan de duur (shear). Echter, op basis van de resultaten is het mogelijk om shear en compressie onderling uit te wisselen als het gaat om het cement herstel te verhogen. Daarom kan een grote maat goedkope shear in een autogene molen de noodzaak van dure compressie in een breker elimineren. Variatie in de sterkte van het betonafval kan worden gecompenseerd door eenvoudige veranderingen in de molen, zoals de verblijftijd en de bedhoogte.

Onderzoek naar de relatie tussen de C2CA ingangsvariabelen en productkwaliteit wordt gegeven in hoofdstuk 5. De belangrijkste factoren van de C2CA werkwijze die de eigenschappen van RG of RGB beïnvloeden zijn het type afvalbeton (Parent concrete = PC), de intensiteit van autogeen malen (het veranderen van de hoeveelheid afschuiving en compressie in de molen) en het scheidingspunt van de ADR (gebruik van +2 mm of +4 mm RG in het nieuwe beton). Om de studie uit te voeren werden eerst drie typen beton die het meeste gangbaar zijn in de Nederlandse markt gestort tot en hun verse en uitgeharde eigenschappen werden getest. Na ongeveer één jaar harding werden deze beton monsters onafhankelijk van elkaar gerecycled, aldus variërend in het type PC en qua intensiteit van het autogeen malen. Experimentele variabelen resulteerden in de productie van acht soorten RG. De fysische, mechanische en duurzaamheid eigenschappen van het geproduceerde RG werden getest en het effect van de experimentele variabelen op hun eigenschappen onderzocht. Volgens de resultaten is het type PC een zeer belangrijke parameter voor de uiteindelijke eigenschappen van RG in vergelijking met de intensiteit van het malen. Bovendien werd opgemerkt dat variatie in de intensiteit van malen vooral invloed heeft op de eigenschappen van RG geproduceerd met een lagere sterkte PC. Volgexperimenten onderzochten de prestaties van de verschillende soorten RG in nieuw gerecycled beton. Vier soorten RGB werden geproduceerd op basis van het gewijzigde recept van hun overeenkomstige PCs (vergelijkbaar met de in hoofdstuk 2 genoemde route). Bi de aanpassing van de recepten werd rekening gehouden met de waterabsorptie en de dichtheid van het RG terwijl de hoeveelheid toegepaste cement en de consistentie klasse hetzelfde bleven als voor de overeenkomende PC. Experimentele resultaten tonen aan dat de druksterkte van alle geproduceerde RGB monsters hoger waren dan die van hun PC, vooral in de vroege sterkteontwikkeling. Dit liet nogmaals de spectaculaire potentie van het gebruik van RA zien. RGB zou deze unieke eigenschap door de hedendaagse vraag in de bouwsector naar fast track werk en de mogelijke tijdsbesparing voor de prefab elementen productie kunnen benutten, om het sociale bewustzijn in de richting van de toepassing van dit waardevolle materiaal te verbeteren. De toenemende mate van druksterkte voor verschillende RAC bleek voornamelijk beïnvloed door het type PC en de intensiteit van het autogene malen. Van de verschillende intensiteiten van het autogeen malen levert de gemiddelde shear en compressie de beste eigenschappen op voor RG en RGB. Goede prestaties van RGB inclusief ook de 2-4 mm ADR fractie bevestigt de mogelijkheid om het scheidingspunt van de ADR op 2 mm te zetten.

Uit de resultaten van de eerste case study van het C2CA project bleek dat het houtgehalte in de 4-16 mm gerecyclede granulaten ruim binnen de strikte grenzen van de EU-norm is. Er zijn echter nog steeds grote zichtbare stukjes hout en kunststof in de +16 mm RA fractie die, weliswaar binnen de normen vallen, maar niet aan de eisen van gebruikers voldoen. Om dit probleem op te lossen is in hoofdstuk 6 de haalbaarheid van de toepassing van twee bestaande technologieën (nabij-infrarood sensor sortering en wind ziften) ter verwijdering van verontreinigingen onderzocht. Daarnaast is het effect van autogeen malen op de grootte van bepaalde contaminanten in dit hoofdstuk bepaald. Resultaten tonen aan dat het industrieel autogeen malen het massapercentage verontreinigingen groter dan 5 mm met 30% vermindert en de verontreiniging naar de fijne fractie verschuift. Er is een duidelijk effect op de verkleining van baksteen door het malen. Een soortgelijke trend kan worden gezien voor hout verontreinigingen, maar in mindere mate. Het is gebleken dat de combinatie van twee technologieën (NIR sensor sortering en wind ziften) de meeste verontreinigingen van +16 mm RA zal verwijderen.

Het C2CA proces is in staat om hoge kwaliteit gerecyclede granulaten te produceren voor structurele toepassingen. Echter, om de kring met C2CA betonrecycling te sluiten, is er behoefte aan recycling en verbetering van de fijne fractie uit de ADR die uit bijna 40 gew.% van het gehele gebroken afvalbeton bestaat. Het oplossen van de problemen met fijne fracties van beton wordt bepaald door het succesvol verwijderen van zeer kleine deeltjes (0-0.250mm) en contaminanten. Gezien de natte en plakkerige toestand van de fijne gemalen betonfracties lijkt een verhittingsstap in het recyclingproces onvermijdelijk om het proces robuust te maken.

Laboratoriumproeven werden uitgevoerd om de invloed van verschillende niveaus van verhitting en malen op de terugwinning van het uitgeharde cement en zand uit de gehydrateerde en verontreinigde fijne fracties van betongranulaat te onderzoeken. Een Heating-Air classification system (HAS) werd ontworpen en gebouwd op laboratoriumschaal. De combinatie van warmte en zifting in de HAS resulteerde in een behoorlijke scheiding van fijnere fracties (0-0.250mm) uit grovere fracties, terwijl het tegelijkertijd de cementbinding in de materialen verzwakte.

Het malen van de grovere productfractie van HAS in een kogelmolen verbeterde de bevrijding van de geharde cement. De experimenten tonen aan dat het verwarmen van het materiaal op 500 °C voor een duur van 30 seconden resulteert in een belangrijke vermindering van de maaltijd. Dit is belangrijk voor de maalkosten en om de productie van nieuwe fijne silica tijdens het malen te voorkomen. Bij het vergelijken van verschillende temperaturen voor de efficiëntie in de terugwinning van gehard cement, zand en het verwijderen van verontreinigingen blijkt 500 °C de meest geschikte temperatuur. De kwaliteit van de materialen uit het voorgestelde recycle proces voldoet aan de eisen van de markt en de bestaande normen. De dichtheid en wateropname van het geproduceerde zand voldoet prima aan de meest restrictieve normen. Bovendien tonen de experimentele resultaten dat de verontreinigingen volledig worden verwijderd door het materiaal te verwarmen op 500 °C. Het verschil tussen de terugwinningsgraad van het cement in de fijne fracties na verhitting van 500 °C en 750 °C is klein. Dit is een andere reden om de verhittingstemperatuur tot ongeveer 500 °C te beperken. De fractie 0-0.125 mm geeft altijd het hoogste percentage van CaO aan, en dus ook het hoogtse percentage gehard cement. Het gehalte CaO in de geproduceerde fijne fracties is vergelijkbaar met de hoeveelheid CaO in een lage kwaliteit kalksteen. Gezien de gewenste chemische samenstelling vanuit de cementindustrie is het mogelijk om de fracties 0-0.250mm of 0-0.125mm die rijk zijn in het geharde cement toe te passen.

Door hergebruik van het verharde cement geproduceerd door HAS zal het nu vrijkomen van het chemisch gebonden CO_2 uit kalksteen worden verminderd met een factor drie. Op basis van de bemoedigende resultaten en de bewezen principes zal een proef opzet ontwikkeld worden voor grootschalige recycling van fijne fracties gebroken beton in het EU VEEP project.

Vervolg Onderzoek

Hoewel dit proefschrift voornamelijk was gericht op de productie van verbeterd gerecycled grind, is er aan het einde van het onderzoek ook een proof of concept op TRL3 uitgevoerd voor een proces om de geharde cementpasta en verontreinigingen uit fijn gerecycled zand los te maken. Dit proof of concept vormt het uitgangspunt voor de nieuwe HAS technologie, een innovatie die wordt uitgevoerd in het Horizon 2020 VEEP project, gericht op het verschuiven van de stand van technologie van-TRL3 naar TRL5 / 6.

Daarnaast wordt er verwacht dat de nieuwe HAS technologie gerecycled zand en aanvullende cementgebonden materialen zal produceren voor de productie van nieuwe beton. De ADR-technologie zal ook worden aangepast aan de recycling van lichtgewicht afvalbeton en de combinatie van ADR en HAS technologie voor gelijktijdige productie van grove en fijn gerecycled zand zal een innovatieve oplossing in VEEP zijn.

Volgens een ruwe schatting wordt er op dit moment minder dan 5% gerecycleerd beton aggregaat gebruikt in nieuwe beton productie. Toch zijn vervangingsniveaus doorgaans toegestaan tot 20% tot 30% van de grove fractie van het beton aggregaat met acceptabele effecten op de visuele kwaliteit, verwerkbaarheid, druksterkte en duurzaamheid van de mortel en beton. Uit dit proefschrift is gebleken dat het ge-

bruik van de ADR technologie kan leiden tot een hogere kwaliteit gerecycled grind voor het gebruik ervan in beton, op voorwaarde dat vocht absorberende fijne fracties en verontreinigingen effectief uit de grove fracties zijn verwijderd.
Dat feit kan zelfs leiden tot een superieure druksterkte wat nieuwe mogelijkheden voor de bouwsector opent. Het verkregen beton verhardt veel sneller dan het beton van natuurlijk aggregaat, terwijl dezelfde hoeveelheid cement wordt gebruikt. Het zou de prefab industrie de mogelijkheid geven om het gebruik van aanvullend cement of additieven te verminderen en de productiviteit van de bestaande installaties te verhogen. Het gebruik van fijne gerecyclede betonfracties in nieuwe betonproductie is nog steeds beperkt door hoge waterabsorptie, lage dichtheid en de aanwezigheid van verontreinigingen. Zoals eerder genoemd, toonde de nieuwe HAS technologie aan dat gerecycled zand (met de absorptie waarden onder 3% en zonder organische fracties) en mogelijk cementpoeder onder 0,25 mm kan worden geproduceerd. Het effect van deze gerecyclede fracties op cementgebonden materialen en nieuwe beton moet nog worden onderzocht.

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Somayeh Lotfi
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Somayeh (Somi) Lotfi was born in Karaj, Iran on September 9, 1982. She received her MSc degree in Materials Engineering, University of Science and Research, Tehran and joined for a while the industry in Iran. She got appointed as a PhD candidate at Delft University of Technology in July 2011. Because of her interest and enthusiasm in the field of building materials and construction and demolition waste recycling, in parallel with her PhD research, she attempted (individually or as a team member) to feed her innovative ideas into new research proposals which resulted in receiving new granted projects such as VEEP (Horizon 2020 EU project), construction and demolition waste recycling and management in Mongolia (a SWITCH-Asia II- EU project) and a 3TU project (Robotically driven construction of buildings).
By the moment this dissertation is finished, her current scientific research and professional activities focus on the recycling and re-use of building materials, in particular recycling of end of life concrete into new concrete within HISER and VEEP projects and she is the project leader of the SWITCH-Asia II-EU project of the Resources and Recycling group. She is also actively involved in developing online courses for knowledge transfer in the field of building materials recycling and management.

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Despite the urgency of creating a sustainable solution for end of life concrete waste, there has not been a large driving force for recycling it into prime grade materials. This low motivation has a root in existing cultural, environmental, political and economic constraints. For concrete to concrete recycling most of the time a lack of economic benefits puts obstacles for the technology and the business model. This indicates that currently the market for concrete recycling may not be large enough and needs innovations to create more attractive products. The C2CA concrete to concrete recycling process delivers such innovations.

The present research work investigated and developed the C2CA concrete recycling process for recycling of end of life concrete to both recycled aggregates, with a quality equivalent to natural aggregates and a hardened cement rich stream for low-CO_2 cement production and other binder products.

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