Characterization of recycled concrete aggregates from construction and demolition wastes

Bachelor thesis

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by

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TU Delft

Abstract

Construction and demolition waste form a significant problem in terms of environmental pollution and material depletion. Concrete, as part of construction and demolition waste, is already responsible for 9% of the total anthropogenic carbon dioxide emissions. Consequently, it is important to alleviate the environmental stress of concrete by replacing virgin aggregates and cement by recycled aggregates and liberated cement. This study determines how the properties of recycled aggregates and virgin (new) aggregates compare for using recycled aggregates in a new concrete mixture.

Recycled aggregate properties are examined by performing a variety of experiments, namely water absorption and specific gravity, Los Angeles abrasion, flakiness and shape index and compressive strength. Each experiment describes a different characteristic of the aggregates creating a clear picture of their properties. The properties of virgin aggregates have been obtained from literature.
In addition, a milling method has been examined as a possible new step in the recycling chain for liberating cement paste from the fine recycled aggregates.

Water absorption and interfacial transition zone formed problems for the recycled aggregates, but they show excellent properties in terms of compressive strength, resistance to abrasion, grain interlocking and shape characteristics.
While very different from each other, recycled aggregates show very good properties when compared to virgin aggregates giving them potential to be used in new concrete mixtures.

Preface

This thesis describes 'Characterization of recycled concrete aggregates from construction and demolition wastes.' This thesis has been written in the frame of finishing my bachelor at the TU Delft. From february 11th until april 9th I have been working on research and writing this report.

I would like to thank a number of people who supported me during my research and the preparation for this thesis. First of all dr. A. Gebremariam who helped me to define my research question, always helped me to find solutions for sometimes difficult problems and encouraged me to complete my research. I would also like to thank my accompanists and supervisors for the good advises they have given me.

Finally, I would like to express my gratitude to Ooms constructions, Van de Kraats bouw BV and the TU Delft who gave me the opportunity to perform experiments and gain knowledge for this research...

T. van Rijswijk
Delft, April 2019

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List of abbreviations

ADR	Advanced Dry Recovery
C&DW	Construction and demolition waste
EoL	End of Life
HAS	Heating Air and classification System
ITZ	Interfacial transition zone
LA	Los Angeles
PSD	Particle size distribution
RA	Recycled aggregates
RAC	Recycled aggregate concrete
VA	Virgin aggregates
VAC	Virgin aggregate concrete
wcf	Water cement factor
wt%	Weight percentage
XRD	X-ray diffraction
XRF	X-ray fluoscerence

1

Introduction

For many years the concrete production industry has been active for creating a wide variety of constructions and more. Although concrete is a very useful construction material, it is also a very polluting material. Not in the sense that the material itself is polluting, but the production chain is polluting. Concrete and its production leave a large CO_2 footprint. The cement industry only, as cement is part of a concrete mixture, is responsible for 5% of the total worldwide anthropogenic CO_2 emissions [Betonhuis, 2019].

The CO_2 footprint needs to be reduced. By recycling concrete and demolition waste (C&DW) this footprint can be reduced. In this report, the outcome of research about the properties of recycled aggregate concrete (RAC) will be compared to virgin aggregate concrete (VAC) in order to evaluate the usability of RAC in a new concrete mixture. This report will answer the question when recycled aggregates can be used in a new concrete mixture without loss of desired properties.

The composition of the report is as follows. Chapter 2 introduces and analyses the problem. Chapter 3 is about the objective of the report. Chapter 4 delivers background information about concrete and concrete recycling machines. Chapter 5 examines both recycled aggregate properties for comparison with virgin aggregates and liberation of cement paste using a milling method. The report ends with the conclusion and recommendations.

2

Problem analysis

This chapter describes the full problem analysis. First some background information is given in §2.1. The problem itself and the importance of this research is described in §2.2.

2.1. Background

What is concrete?

Concrete is a very common used construction material. It consists of a mixture of aggregates, like gravel and sand, combined with water and cement. In 1824, J. Aspdin created Portland cement [de Vree, 2019]. Ingredients in Portland cement are mostly calcium oxide (CaO) and silicon dioxide or silica (SiO_2). Calcium oxide is found in many varieties, like chalk or limestone. Silica is found in mineral forms in argillaceous clay or shale [Gan, 1997]. Processing takes place in a Portland cement kiln in, for example, a wet process as can be seen in figure 2.1.

Cement production process

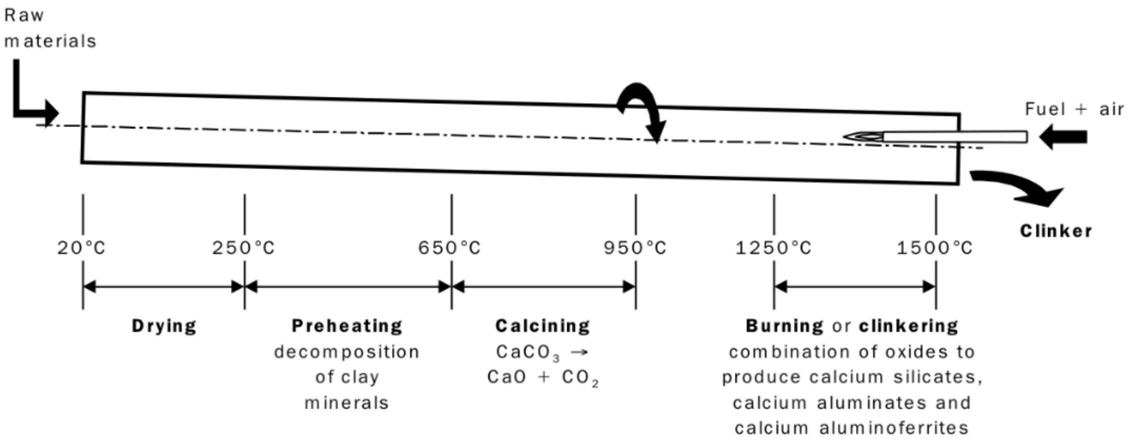


Figure 2.1: Production of portland cement using a kiln

Application

When cement is combined with water, sand and aggregates in a good composition, concrete is created. Concrete is used in buildings, car parks, countless architectural eyesores, roads and in a lot more ways. Testing concrete started at 1836 in Germany [Concretenetwork, 2019]. In the 19th Century, concrete was used for industrial buildings and home constructions. Steel rods were added as reinforcement and added additional good properties to the materials' behaviour [Pepin, 2017].

Advantages

Concrete is an important construction material that is used a lot. Due to the fast strength development and good initial strength, concrete is a useful material when it comes to constructions. But what about the influence it has on the environment?

2.2. Problem statement

Problem

Concrete is produced at a rate of 2 billion tonne quantities per year and this is expected to increase drastically in the upcoming decades. Both the cement industry and depletion of raw materials form a large problem. Only the worldwide cement production is responsible of an annual emission of 1.45 ± 0.20 Gt carbon dioxide, equivalent to 5 % of the total anthropogenic carbon dioxide emissions [Andrew, 2018]. The total emission for concrete production becomes even greater when transportation, machinery and material collection are included. According to Purnell [2013] the total emission for concrete emission is equivalent to 9 % of the total anthropogenic carbon dioxide emissions.

Cause

After J. Aspidin developed the first steps in making Portland cement, cement plant laboratories took over for a common way of producing cement. Due to the chemical reaction in the production of the main component of cement, clinker, and the usage of fossil fuels to generate enough heat to make these chemical reactions happen, emission of carbon dioxide occurs. According to Baxter and Walton [1970], the production of 1 ton cement in the EU yields 0.7t carbon dioxide [Cementenbeton, s.d.]. In other continents, this can be even greater.

Possible solutions

The whole cement and concrete production chain need drastic improvements in terms of reducing the carbon footprint and preventing depletion of the raw materials used for making concrete. A possible outcome can be a functioning recycling chain. In the recycling process used in this report, the combination of Advanced Dry Recovery (ADR) and Heating Air and classification System (HAS) are used to separate End of Life (EoL) concrete into possible products for a new concrete mixture.

3

Objective

This chapter is about the objective of this research. It starts with the general objective of the research in §3.1. Then, §3.2 describes the methodology and structure of the report.

3.1. Objective

This report describes the potential of recycling EoL concrete as a method to alleviate the environmental stress of concrete. It examines the impact of a closed concrete production cycle on the environment by answering the following research question: "*How can properties of recycled aggregates from construction and demolition waste be compared to virgin aggregates in order to possibly use them in a new concrete mixture?*". The following objectives are formed from this research question:

- Compare properties of virgin aggregates (VA) with recycled aggregates (RA) processed by ADR
- Examine a method called milling as a potential recycling step to liberate cement paste from the fine fraction of RA from HAS output

3.2. Methodology and structure

The first aim is to compare properties of VA and RA. For VA, literature is be used to find a reference for the average properties. This is to reduce the size of the research, since performing experiments on VA would be too much. For determining properties of RA, experiments are performed and the results of these experiments are examined and compared to the outcome of the VA literature results.
The second aim is to research the potential of milling, which is aimed to liberate cement paste from the surface of the fine fraction of the HAS output. The results will show if milling is a potential new step in the recycling chain.
Using all the results, the research question can be answered.

4

Background information

4.1. Properties of concrete

After a service life of several years, a concrete structure will be broken down. This concrete waste is called EoL concrete. Before discussing about EoL concrete, it is important to know what concrete actually is. This paragraph describes the materials within concrete in §4.1.1. §4.1.2 continues with general properties of concrete and §4.1.3 describes the transition from C&DW to EoL concrete. Finally, §4.1.4 describes the general problems with EoL concrete.

4.1.1. Materials in concrete

This report is all about concrete and recycling, so it is useful to gain a little knowledge about the materials in concrete itself. Concrete is a composite material consisting of a binding medium with fragments of aggregate within. This binder is cement paste, consisting of cement and water in a pre-calculated amount. The aggregates in concrete can be, for example, river stones that are sieved to different sizes or mountain rocks that are crushed and then sieved. Sometimes, admixtures are used in concrete to modify the properties to the customers wish.

4.1.2. General properties

Overview

With concrete, basic properties are:

- Segregation
- Consistency
- Workability
- Bleeding
- Water absorption
- Water cement factor
- Interfacial transition zone
- Grain interlocking
- Abrasion

Explanation on these properties will be described step by step. These properties can be different for each mix, depending on what the customer wants. This is important to understand the importance of examining RA and why it should be compared to VA.

Segregation

Segregation must be prevented, since it is the separation of particles in a mix, causing a non uniform mixture. This may be caused by differences in specific gravity or size of constituents of concrete. Improper mixing, placing and consolidation may also lead to segregation.

Workability

Workability is the most important property of fresh concrete. A mixture is said to be workable if the mixture is relatively easy to transport, place, compact and finish without causing segregation. Without workability, concrete will not be workable and this creates an inconsistent mixture with unpredictable (strength) properties. Workability is determined by measuring consistency.

Consistency

Consistency is measured using a slump test. A slump test explains the ease with which the concrete flows during placement. The slump test consists of a cone which is filled with concrete, then it gets lifted and the concrete will settle a little. The amount it settles, determines its consistency. Since consistency is related to workability, a non-consistent mixture also creates an inconsistent mixture with unpredictable (strength) properties.

Bleeding

Bleeding is the tendency of water to rise to the surface of fresh concrete. This is caused by the aggregates which are not able to hold the mixing water when they settle down. The concrete might get weak when it is bleeding. Bleeding can be prevented by increasing the fineness of cement, adding pozzolanic admixtures, reducing water content or change the duration of vibration.

Water absorption

Water absorption of aggregates is determined by measuring the increase in mass of an oven-dried sample which is immersed in water for 24 hours. High water absorption should be compensated for since this may effect the workability of a concrete mixture. According to Neville [2002], there is no clear-cut relation between strength of concrete and water absorption, but the pores at the surface of the aggregate affects the bond between aggregate and cement resulting in some influence on the strength of concrete.

Water cement factor

The water cement factor (wcf) is the ratio of water present in the fresh concrete to the quantity of cement. According to S. Popovics [2008] concretes provide:

1. Lower strengths with higher water-cement ratios
2. Higher strengths with lower water-cement ratio; and
3. The same strengths with identical water-cement ratios, regardless otherwise of the concrete composition.

Interfacial transition zone

The interfacial transition zone (ITZ) is the microstructure of the cement paste modified in the vicinity of the aggregate particles [J.P. Ollivier and Bourdette, 1995]. Hydration in the vicinity of aggregate grains differs from reactions in the bulk paste since the wcf is locally higher. Also, growth and nature of hydrates may be influenced by the surface and chemical nature of aggregates. The excess of porosity is the cause and consequence of ITZ existence. When particles are unable to become closely packed against larger particles of aggregate there will be less cement present to hydrate and fill voids [Neville, 2002]. This means that the interface zone has higher porosity than the hydrated cement paste, with a possible lower compressive strength as a result.

Grain interlocking

The amount of grain interlocking determines the bonding of aggregates. The bond between aggregates and cement greatly influences the concrete strength, especially flexural strength.

When aggregates permit no penetration of the surface of the particles then they will not have a strong bond. Crushed particles will have better interlocking, creating a stronger bond [Neville, 2002].

Abrasion

Abrasion is the ability of a surface to resist being worn away by rubbing or friction [Scott and Safiuddin, 2015]. The resistance depends on cement paste hardness, aggregate hardness and aggregate/paste bond. Abrasion relates to strength and should be taken into account by using a low wcf and calculating for high strength to resist stresses coming from abrasion.

4.1.3. From C&DW to EoL concrete

C&DW is generated waste during both the construction and demolition process [C.S. Poon, 2001]. This waste can, most of the time, be classified into different categories. For this report the building demolition waste is the most important. Typical composition of building demolition waste and building waste can be seen in table 4.1 below:

Table 4.1: Composition of building and demolition waste [EPD, 1991]

Consituent	**Percent**	
	Building demolition waste	**Building waste**
Asphalt	1.61	0.13
Concrete	19.99	9.27
Reinforced concrete	33.11	8.25
Dirt, soil, mud	11.91	30.55
Rock	6.83	9.74
Rubble	4.95	14.13
Wood	7.15	10.53
Bamboo	0.31	0.30
Block concrete	1.11	0.90
Brick	6.33	5.00
Glass	0.20	0.56
Other organics	1.30	3.05
Plastic pipe	0.61	1.13
Sand	1.44	1.70
Trees	0.00	0.12
Fixtures	0.04	0.03
Junk	0.07	0.24
Metal (ferrous)	3.41	4.36
Total	**100.00**	**100.00**

According to Bakker [2018] the first step when it comes to demolition of buildings is to plan the whole structure in order to obtain optimum recovery of recyclables. The next step is to strip and clean the building. Here, EoL materials are stripped from the buildings, like wood, plastics, glass etcetera. Then it is time for the demolition stage, with three deliverables:

- Steel reinforcement bars and profiles
- Coarse concrete and steel rebar
- Masonry and gypsum

The second delivery, coarse concrete and steel rebar, is what is known as EoL concrete.

4.1.4. Problems with EoL concrete

When a heap of recycled aggregates remains after processing EoL concrete, it can be processed even further. Within the concrete recycling chain, the fraction of materials in size of 0-12mm form a problem, since it seems economically unfeasible to use this moist granular material [de Vries, 2017]. This problem is caused by the presence of both moisture and fine particles. One of the possible solutions would be to dry the material, but this would introduce a large energy consumption and health risks by formation of fine dust. Another method would be to wet the material, so it can be classified efficiently. But then again, the water needs to be removed after classification and this proves to be difficult for the fine fraction. Recycling machines as the Advanced Dry Recovery (ADR) and Heating Air and classification System (HAS) are developed to remove these problems and will be described in §4.2.

4.2. From EoL concrete to recycled aggregates

After C&DW has been transformed to EoL concrete, the next step is to transform the EoL concrete to recycled aggregates. The processing steps of this transformation can be found in §4.2.1. §4.2.2 describes a special machine, namely the ADR, for separating the EoL concrete into different aggregates. After the ADR, the HAS is used for even better classification and this is described in §4.2.3. The separation products from these machines are discussed in §4.2.4. Finally, another recycling method will be described in §4.2.5.

4.2.1. Processing steps of EoL concrete to recycled aggregates

After concrete demolition waste has been turned into EoL concrete, it is time to process this material even further until recycled material is obtained. This process is as follows:

1. Smart demolition of constructions, with clean concrete containing as little contaminants in the concrete as possible
2. Crushing concrete to remove other contaminants and steel rebar with crushed mineral as a result
3. Let crushed mineral go through the C2CA recycling technology, namely the ADR and HAS
4. Recycled material product

4.2.2. Advanced dry recovery (ADR)

The ADR is a two-step dry process, of which visualisation and deliveries can be seen on figure 4.1. For a real image of the ADR, see figure F.1 in appendix F.

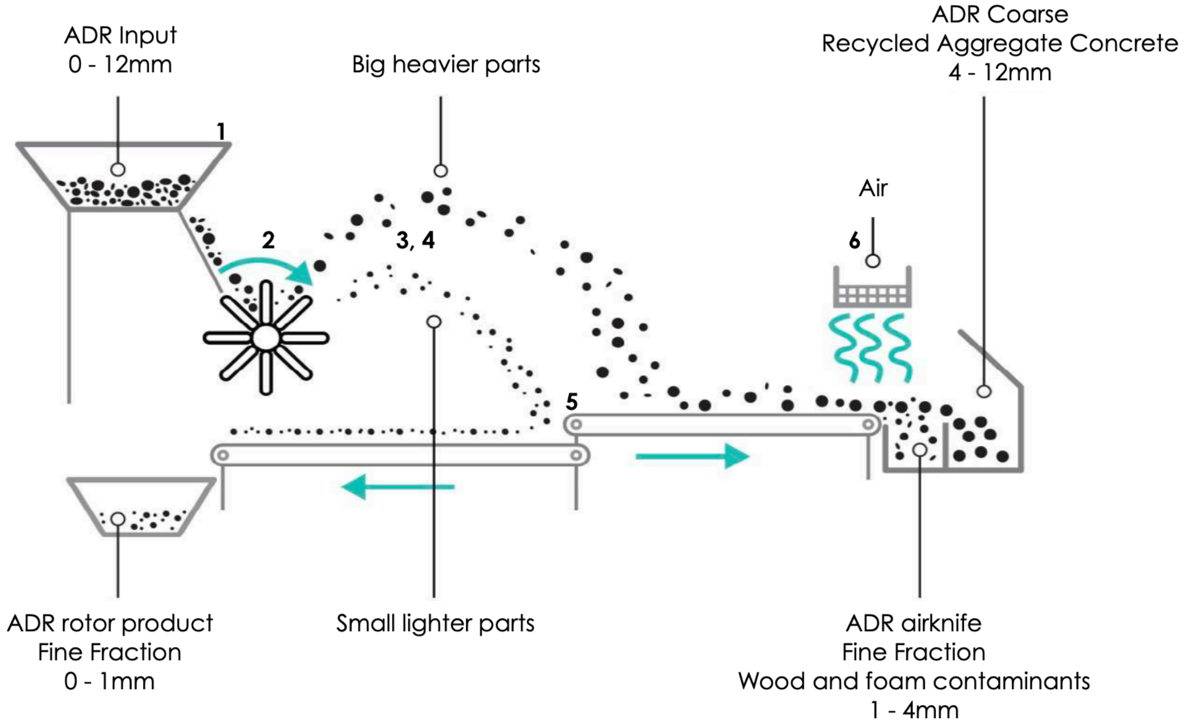


Figure 4.1: Advanced dry recovery, [Di Maio, 2016]

The ADR has got the following process:

1. Input of aggregates in size 0-12mm
2. A spinning rotor breaks water bonds between grains, after which small and big grains are separated via ballistic separation. Initial impact compacts the grains and rearranges them. The blade will be in contact with all grains and brings them to a horizontal velocity. After further rotation, horizontal velocity of the blade decreases and inertia forces grains to become airborne.
3. Grains are airborne and diverge into a fan. This pulls the grains further apart whilst breaking the water bonds.
4. Grains are subjected to air drag whilst air borne. The larger this drag is, the closer to the rotor the grains will fall. Small grains have less kinetic energy and a relatively larger surface-to-volume ratio than large grains, so they loose kinetic energy proportionally faster. This kinetic energy is proportional to mass, so low-density and small grains will have proportionally less kinetic energy. This means that large and heavy grains travel far, and small and light grains travel less far.
5. Grains are separated by a calculated cutoff point where one belt contains the ADR rotor product (0-1mm) and the other belt continues with the rest of the material
6. The airknife is the last process step of the ADR. The airknife blasts air down, separating the coarse fraction (4-12mm) and the remaining fine airknife fraction (1-4mm)

After the ADR has processed the material, there are three separation deliveries. One delivery is the coarse aggregate in size 4-12mm. The other two deliveries are fine aggregates in size 0-4mm. The latter will continue to the HAS.

4.2.3. Heating air and classification system (HAS)

The HAS is a machine which uses a combination of high temperature and air flow to dry and separate the fines (0.25-4mm) from the ultra fines (0-0.25mm). A visualisation of the HAS can be seen on figure 4.2. For a real image of the HAS, see figure F.2 in appendix F.

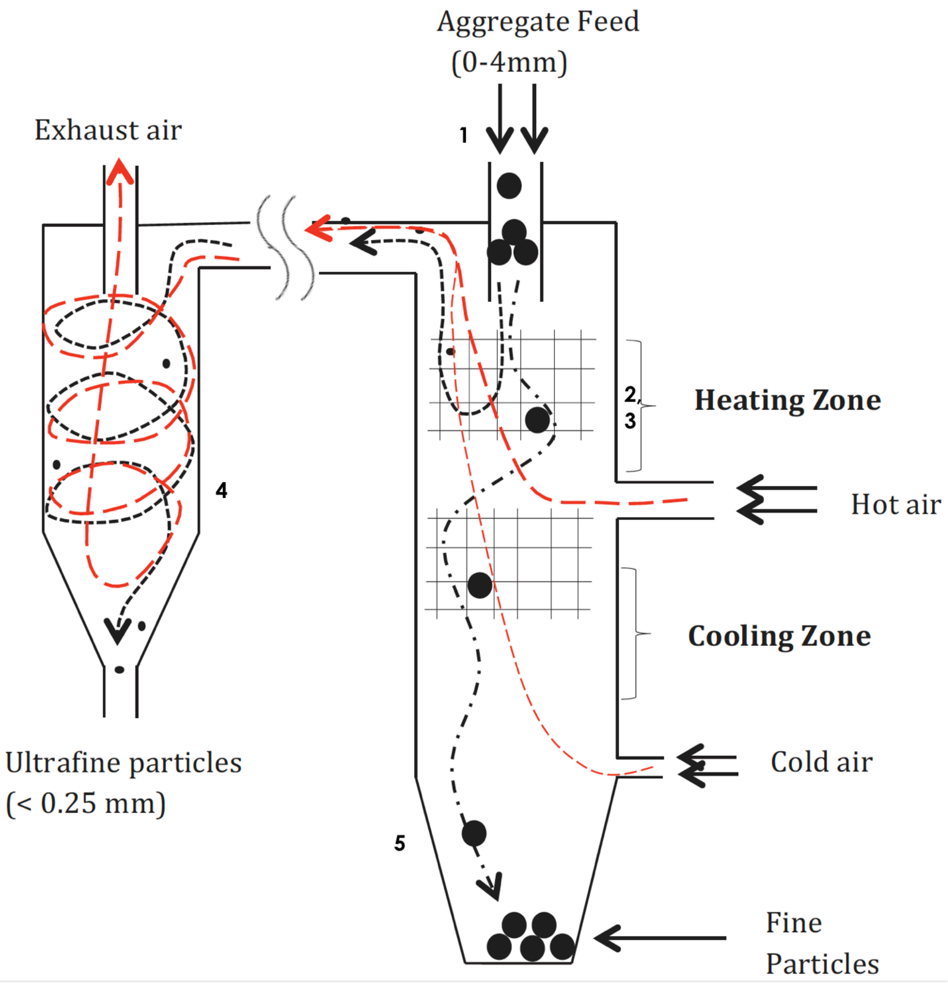


Figure 4.2: Heated air and classification system, [Di Maio, 2016]

The HAS has got the following process:

1. Input of aggregates in size 0-4mm
2. Material flows through different chambers into the heating zone
3. Material is heated and dried in a hot air flow
4. The ultra fine particles (0-0.25mm) follow the air flow into the left chamber and cool and fall down through the cyclone
5. The fine particles (0.25-4mm) enter the cooling zone, cool down and fall down to the bottom of the main chamber

After the HAS has processed the material, there are two separation deliverables. One delivery is the fine aggregate fraction in size 0.25-4mm. The other delivery is the ultrafine fraction in size 0-0.25mm. The HAS is still a work-in-progress machine, the throughput is yet unknown. However, the machine promises low carbon dioxide emissions and high efficiency for recycling the (ultra)fine fraction of concrete aggregates.

4.2.4. Separation products

Both the ADR and HAS are very promising techniques for recycling end of life concrete. The ADR starts with the materials in size 0-12mm and delivers three different separation deliverables:

1. Fine rotor fraction (0-1mm)
2. Fine air knife fraction (0-4mm)
3. Coarse fraction (4-12mm)

The coarse fraction is a good working aggregate for a new concrete mixture, but the fine fraction (rotor and air knife product) first needs to go through the HAS for further processing. The HAS has two different separation deliverables:

1. Ultra fine fraction, containing cement (0-0.125mm)
2. Fine fraction (0.125-4mm)

So after going through the two processing machines, end of life concrete with size 0-12mm will be turned into three different end products:

1. Ultra fine fraction, containing cement (0-0.125mm)
2. Fine fraction (0.125-4mm)
3. Coarse fraction (4-12mm)

Since the properties of these end products are important for reusing them in concrete mixtures, it is important to do further investigation on their properties. These properties are determined using experiments. The outcome of these experiments, along with a comparison to VA is described in chapter 5.

4.2.5. Other method

Since the ADR and HAS are not the only recycling chains, another example for recycling will be given below. The smart crusher 1 is another way of recycling aggregates and liberating cement paste from the aggregates.

Smart crusher 1

The smart crusher 1 is a method from H.J.H. Brouwers [s.d.]. The smart crusher 1 is a prototype machine that is an alternative to a conventional crusher. The following steps were performed for the whole cement liberation analysis:

1. Crush concrete of age 91 days with the smart crusher to obtain aggregates size 0-2mm
2. Compare conventional crusher with smart crusher via PSD and laser granulometry
3. Perform thermogravimetric and differential thermal analysis to determine mass loss with temperature variation and thermal reactions within the sample
4. Perform XRF for oxide composition of the sample

Results

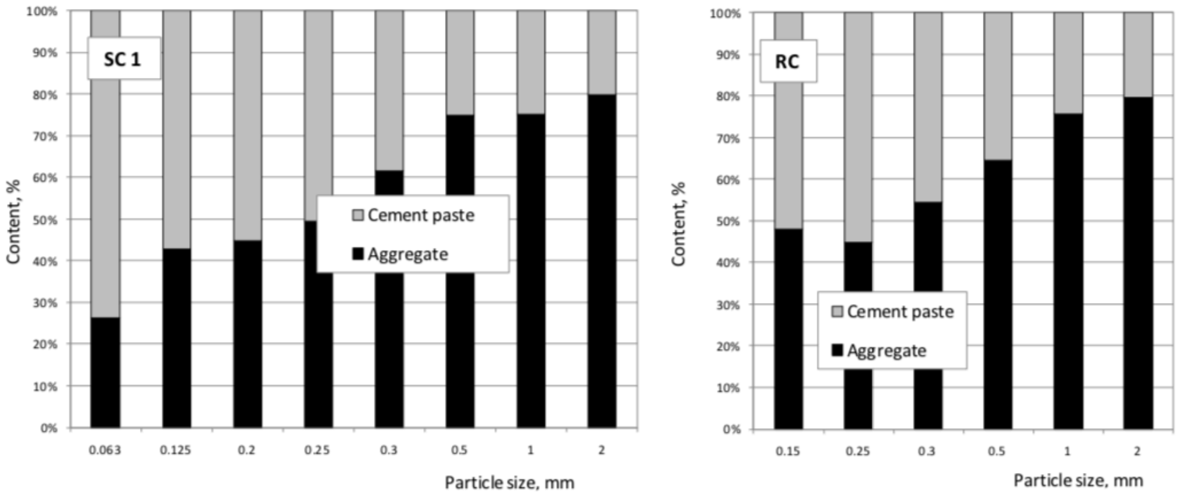


Figure 4.3: Smart crusher versus conventional crusher cement content comparison

The smart crusher showed a much higher cement paste content in the fractions as opposed to the conventional crusher as can be seen in 4.3. The recovery of cement paste in their particle size range improved by a factor 7.5. Via thermal treatment, the slag became dehydrated again when it was treated at 500 or 800 degrees Celsius which can liberate the cementitious ability recycled concrete fines.

5

Research and research results

5.1. Examination of recycled and virgin aggregate properties

Finally, recycled aggregates are obtained. The question that remains is: 'What are the properties of these RA compared to VA'? The examined properties of RA are discussed in §5.1.1. §5.1.2 through §5.1.6 each describe an experiment where a specific material property will be determined and compared to VA.

5.1.1. Properties to be examined

In order to obtain properties, some experiments were executed on the materials originating from the ADR and/or HAS from the processing site in Hoorn (November 2018). The experiments will each be examined in the next sub-paragraphs for determination of some important material properties. All the tests are related to the general properties of concrete and these properties will be included in the experimental results. The following experiments were executed:

- Particle size distribution (PSD)
- Specific gravity and water absorption
- Los Angeles abrasion (LA)
- Flakiness and shape index
- Compressive strength

For each experiment, a sample has to be created. The general workflow for sample preparation can be found in appendix A.

5.1.2. Particle size distribution

Method

One of the first experiments was to determine the particle size distribution of samples from three different processing steps, namely from the ADR input (0-12mm), ADR output fines (0-4mm) and ADR output coarses (4-12mm). The test has been performed conform NEN-EN 933-1:2012(E).

Scope

Determining the efficiency of the ADR via the distribution of particle sizes of aggregates.

Process

The PSD experiment has got the following process:

1. Create a sample with enough, but not too much mass. For this test the samples were between 6 and 8kg
2. Stack sieves from small (0mm or pan) to large (16mm) and put one sample on the highest sieve
3. Sieve for 7 minutes with an amplitude of 1mm
4. Weigh the mass of the material retained on each sieve
5. Make a table of the mass retained and cumulative percentage passed
6. Create a PSD graph

The following samples were used for the PSD:

- B-ADR: Before ADR sample (0-12mm)
- A-ADR1: After ADR sample (0-4mm)
- A-ADR2: After ADR sample (4-12mm)

Figure

The PSD graph can be seen on figure 5.1 below.

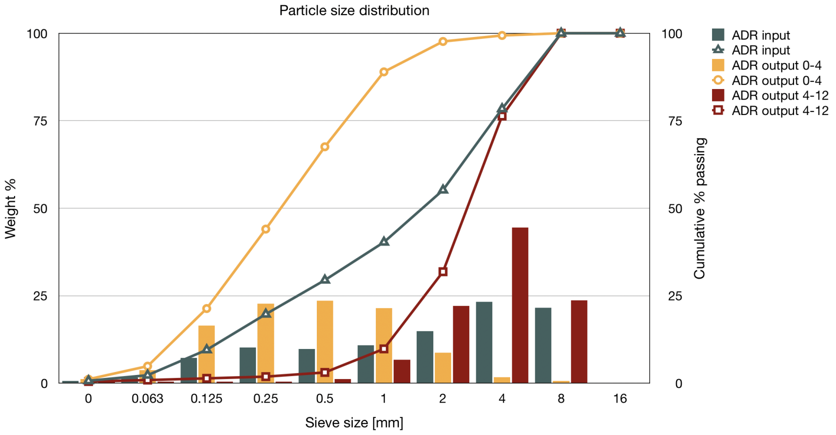


Figure 5.1: Particle size distribution

The bar chart explains the weight percentage (left axis) that is retained on each sieve. The lines represent the cumulative percentage of the material passing (right axis) the specific sieve size (horizontal axis). More specific results can be found in appendix B.

Result

The ADR input is expected to have a particle size distribution conform the design graphs for concrete mixtures. This can be seen in the figure. Since only material up to 12mm has been used for the ADR, it is logical to observe that 100 weight percentage (wt%) of all material passes the 16mm sieve. For the 0-4mm output it is expected that most particles pass through the 4mm sieve. According to the graph, 99.35 wt% of the 0-4mm output passes the 4mm sieve. The graph also shows, 76.33 wt% has been retained sieve size 4mm and up. This means that 23.67 wt% passes through sieve size 4mm and below. Thus, the ADR 4-12mm output contains mostly coarse particles by weight percentage, but it still contains $\frac{1}{4}$ wt% of fine particles below 4mm.

Explanation

The variance in efficiency may be caused by either a wrong cutoff point (as described in §4.2.2) or fine particles sticking and piggy-bagging (riding along) with the coarse particles. Another possible cause could be that fine particles get into the coarse product due to air currents within the ADR.

Conclusion

The ADR works very efficient when it comes to separating fine particles from coarse particles since 99.35 wt% of the coarse fraction are coarse aggregates. However, the fine fraction still contains a quarter of coarse aggregates which lowers the overall efficiency of the ADR. This PSD will be used in §5.1.6 for a concrete mixture, where the coarse fraction of the recycled materials are used in a concrete mixture to determine its compressive strength.

5.1.3. Specific gravity and water absorption

Method

When designing a concrete mixture, the amount of water used in the mix is very important, since it has great influence on the final compressive strength. Therefore, it is vital to know the specific gravity and water absorption of RA in comparison to VA. In this experiment, conform NEN-EN 1097-6:2013, a modified pycnometer method has been used.

Scope

Determination and comparison of specific density and water absorption of RA with respect to VA.

Process

The specific gravity and water absorption test has got a different process for the coarse and fine aggregates, the different processes can be seen in table 5.1 below.

Table 5.1: Processing steps for specific gravity and water absorption test

Processing steps for specific gravity and water absorption test	
Coarse aggregates	**Fine aggregates**
1. Weigh 1kg of coarse aggregate +4mm to remove all fines	1. Take 2kg of fine aggregates in saturated surface dry condition and place 500g (C) into the pycnometer
2. Place sieved sample in vessel and partially fill it with distilled water	2. Partially fill vessel with distilled water and shake to remove entrapped air bubbles. Then completely fill vessel
3. Keep aggregates immersed for 24h, remove air bubbles by gentle agitation and overfill vessel with distilled water Take weight of vessel assembly (A)	3. Weigh pycnometer with its contents(A)
4. Drain vessel, dry surface of coarse aggregates on dry cloths	4. Pour contents of pycnometer into a tray
5. Refill vessel with distilled water and weigh it (B)	5. Fill pycnometer with water and weigh it (B)
6. Weigh surface saturated dry coarse aggregates (C)	6. Decant water from tray into beaker and filter it. Filter containing very fine particles can be put back in the tray
7. Place aggregates in oven at 105C for 24h	7. Place tray in oven at 105C for 24hr
8. Cool the aggregates and weigh them (D)	8. Cool the aggregates and weigh them (D)
9. Calculate the result using A, B, C and D	9. Calculate the result using A, B, C and D

Table

The result of the specific gravity and water absorption experiment can be seen in table 5.1 below, along with experimental results from P. Belin [2014] and Tegguer [2012] for comparison. More detailed results including standard deviation can be found in appendix C.

Table 5.2: Water absorption and specific gravity results

Origin of results	**Water absorption (%)**	**Specific gravity**	**Density (kg/m^3)**
Experimental results			
Fine fraction I	9.66	2.094	2094
Fine fraction II	9.80	2.096	2096
Coarse fraction I	5.21	2.325	2325
Coarse fraction II	5.11	2.256	2256
Coarse fraction III	4.74	2.343	2343
Coarse fraction IV	4.71	2.512	2512
Literature results			
P. Belin recycled crushed coarse	7.0	-	-
P. Belin natural crushed coarse	2.2	-	-
A. Tegguer recycled coarse	4.0	-	-
A. Tegguer natural coarse	0.8	-	-

Result

The water absorption for the coarse fraction is 4.94% on average, which positions it between the results obtained by P. Belin and Tegguer. The fine fraction has got an average water absorption of 9.73 %.

Explanation
What can be seen, is that the average water absorption is higher for the fine fraction than for the coarse fraction. According to Tegguer [2012] ”*This can be explained by crushing effect of aggregates, which can increase pore connectivity, create cracks and generates a water absorption increase coefficient.*” Another possible cause for this higher outcome has to do with the surface-to-volume ratio. All aggregates still have a little cement paste on their surface. Cement absorbs a lot of water, and since the surface-to-volume ratio of smaller aggregates is relatively larger compared to larger aggregates, they will tend to absorb relatively more water.

Another interesting observation is the fact that coarse recycled aggregates' water absorption is significantly higher when compared to natural crushed coarse aggregates. This high water absorption can be explained using specific gravity. Specific gravity can be transformed to bulk density, which explains the mass of aggregate that fills a container of unit volume (for example, how many kilograms of material is needed to fill a container of 1 m^3). A higher bulk density means fewer voids to be filled by the material, thus a lower water water absorption. Since the specific gravity of the RA is in fact lower compared to VA, it seems logical that the water absorption increases. Pores in the recycled aggregates are larger and make it easier for water to be absorbed. The exceptionally high amount of water of absorption for the fine aggregates is obviously due to the presence of ultrafine along with the sample. These ultrafines should have been excluded before testing water absorption. However, the wet nature of the fine fraction makes sieving at 63 microns very difficult.
According to Tegguer [2012] it seems that RA have a longer time of saturation, so water absorption for these aggregates might actually be even higher compared to the outcome of the test.
During the coarse water absorption experiments, a towel was used to dry the aggregates to a surface saturated dry condition. This means that the surface of the aggregate is dry, while the inside of the aggregate is still saturated with water. During the second coarse water absorption test, the aggregates were dried even more with the towel which might be the cause for a lower water absorption during the second test since there is less water on the surface of the aggregate.

Conclusion
The water absorption is, as expected, rather high. This has implications for concrete mixtures, since additional water needs to be added due to this higher absorption. Otherwise, the concrete will not be able to meet the required properties (like compressive strength).

5.1.4. Los Angeles abrasion

Method

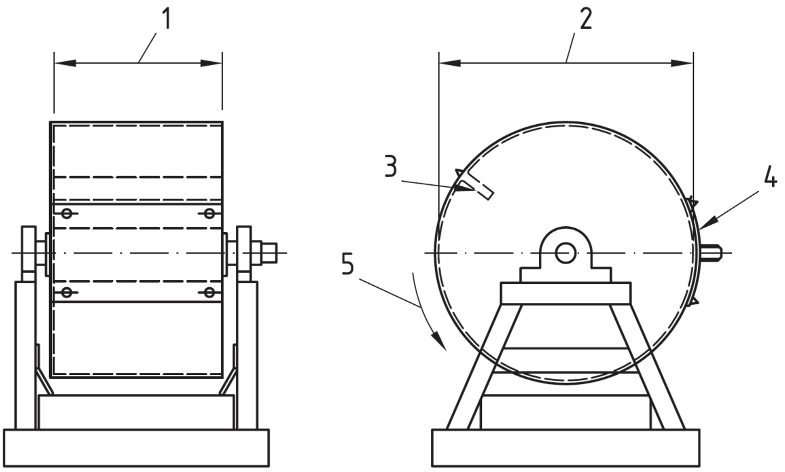
Aggregates undergo wear and tear, so they should be resistant enough to crushing, degradation and disintegration. To investigate these properties, the Los Angeles abrasion experiment has been developed. The Los Angeles abrasion experiment indicates toughness and abrasion characteristics of aggregates. The experiment has been executed conform NEN-EN 1097-2:2010.

Scope

Determining the resistance to fragmentation of coarse and fine recycled aggregates.

Process

A typical Los Angeles abrasion machine can be seen on figure 5.2



Key

1 internal length (508 ± 5) mm
2 internal diameter (711 ± 5) mm
3 shelf
4 cover and opening
5 rotation

Figure 5.2: Los Angeles testing machine [NEN-EN 1097-2:2010]

The experiment has got the following process:

1. Create a test sample of 15kg passing the 14mm sieve and retaining on the 10mm sieve, meeting the following criterion:

   Between 30-40 % passing the 11.2mm sieve
2. Split the sample in three test portions of 5000 ± 5g each
3. Place steel balls and sample in machine
4. Place cover and rotate for 500 revolutions at 31-33rpm
5. Remove material and steel balls, sieve on 1.6mm sieve
6. Calculate Los Angeles coefficient using formula 5.1

The resistance to abrasion is described using the Los Angeles coefficient. This coefficient is built up by describing the mass loss caused by crushing the material via the following formula:

$$LA = \frac{5000 - m}{50} \tag{5.1}$$

where:

LA = Los Angeles coefficient
m = Mass of material retained on 1.6mm sieve

Table

Table 5.3: Los Angeles abrasion loss, references retrieved from Pavement interactive

Type of material	L.A. abrasion loss (wt%)
Hard, igneous rocks	10
Soft limestones and sandstones	60
Ranges for specific rocks	
Basalt	10-17
Dolomite	18-30
Granite	27-49
Limestone	19-30
Quartzite	20-35
Experimental results	
Coarse fraction [10-14mm] average	27.91
Fine fraction [4-8mm] average	26.16
Other research results	
D. El-Tahan new RAC	19.01
D. El-Tahan old RAC	31.80
Limit value for concrete	**50**

Results
As can be seen, the Los Angeles abrasion loss is 27.91% for the coarse fraction and 26.16% for the fine fraction. Detailed results including standard deviation can be found in appendix D.

Explanation
Since RA have already been used in a material and it has got a more porous structure, the resistance to abrasion is expected to be lower compared to VA. This means that a higher LA coefficient is expected for RA. The aggregates used in concrete are mostly classified as granite and limestone. As can be seen, the results fall within general Los Angeles abrasion loss values and are far below the limit value for concrete [Pavementinteractive, 2019]. The results are also comparable to the research from D. El Tahan [2018]. It seems that the LA coefficient increases when the material ages. Since the used material for the experiment is RA which has already been used once, the higher LA coefficient compared to references is logical.

Conclusion
The value of the Los Angeles abrasion test falls within the stated norm which makes the recycled aggregates suitable for a concrete mixture in terms of resistance to crushing, degradation and disintegration.

5.1.5. Flakiness and shape index

Method

External characteristics in terms of flakiness and shape index are important for characterizing aggregates as well. Since a shape for a three dimensional body is difficult to describe, certain geometrical characteristics should be defined for these bodies. From the British standard, the shapes are classified with examples in table 5.4.

Table 5.4: Particle shape classification of BS 812: Part 1: 1975, with examples

Classification	Description	Examples
Rounded	Fully water-worn or completely shaped by attrition.	River or seashore gravel; desert, seashore and wind-blown sand.
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges.	Other gravels, land or dug flint.
Flaky	Material of which the thickness is small relative to the other two dimensions.	Laminated rock.
Angular	Possessing well-defined edges formed at the intersection of roughly planar faces.	Crushed rocks of all types; talus; crushed slag.
Elongated	Material, usually angular, in which the length is considerably larger than the other two dimensions.	-
Flaky and elongated	Material having the length considerably larger than the width, and the width considerably larger than the thickness.	-

Since the proper equipment for testing this conform NEN-EN 933-3:2012 was not available, the flakiness and shape index will be judged by separating a small sample of 100 particles of the 4-12mm fraction from the ADR output into different shape classifications.

Scope

Determination of flakiness index of aggregates.

Figures

Figure 5.3: Flakiness and shape index particles [1/2]

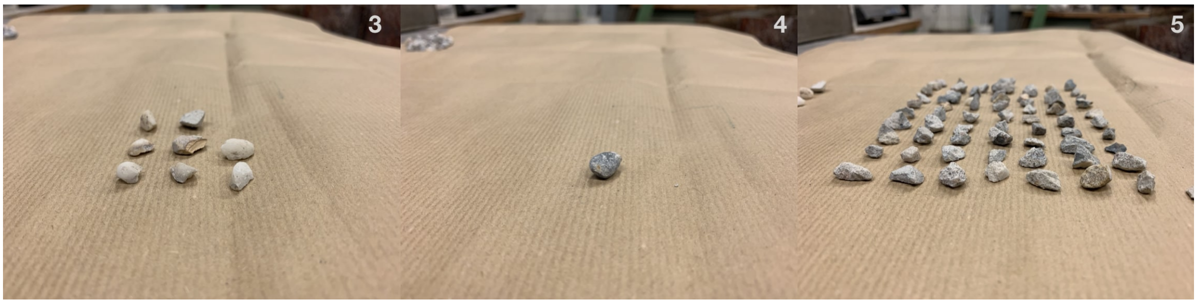


Figure 5.4: Flakiness and shape index particles [2/2]

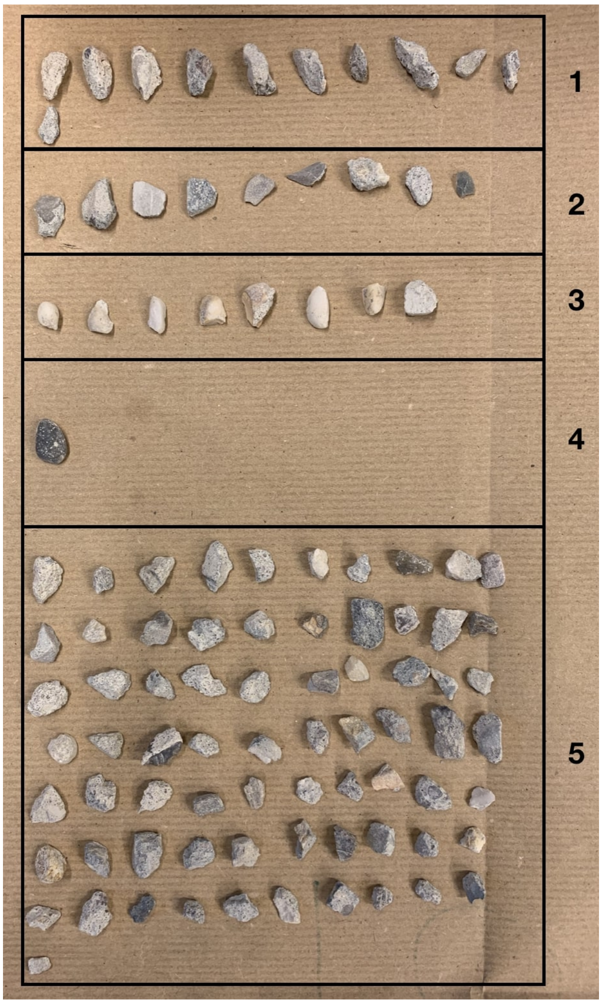


Figure 5.5: Flakiness and shape index overview

Result

The following shapes correspond with the numbers:

- 1. Elongated
- 2. Flaky
- 3. Irregular
- 4. Rounded
- 5. Angular

In table 5.5 below, the amount of particles with their shape is presented.

Table 5.5: Flakiness and shape index results

Shape	Number	Notes
Elongated	11	Feels very rough, a lot of pores
Flaky	9	Dense particles with nearly no pores
Irregular	8	Really smooth edges with nearly no pores
Rounded	1	Very dense and smooth
Angular	71	A lot of visible pores

As can be seen, 11 particles are elongated, 9 are flaky, 8 irregular, 1 rounded and 71 out of 100 particles were found to be angular.

Explanation

Roundness measures relative sharpness or angularity of edges and corners of particles. This is controlled mainly by strength and abrasion resistance. Here, crushed aggregates are used, where particle shape does not only depend on the nature of the parent material, but also on the way of crushing. According to [Neville, 2002] the shape of fine aggregate particles influence concrete mix properties. Angular particles require more water for a better workability. As for coarse aggregates, the particles that depart from equidimensional shape are of interest, namely elongated and flaky. Flaky particles tend to be orientated in one plane, with bleeding and air voids forming underneath as possible result.

Since the majority of the particles are angular, concrete mixture properties can be affected. These particles contain a lot of visible pores and will absorb more water then the other shapes [Neville, 2002]. The elongated and flaky particles account for 20 % of the particles from this sample, which means that bleeding might be introduced due to water and air voids forming underneath these particles due to their orientation in one plane. However, changing the vibration time might compensate for the possible introduction of bleeding.

Conclusion

Based on the shape and flakiness of the particles, RA are suitable to be used in a new concrete mixture. However, a lot of care should be taken in terms of addition of the amount of water and cement because of the large observed pores. Also, the elongated and flaky particles may introduce bleeding so this has to be accounted for by, for example, changing the duration of vibration.

5.1.6. Compressive strength

Method

The RA might seem suitable for concrete mixtures, but can a mixture containing coarse recycled aggregates still perform well? For this, a sequence of compressive strength tests have been performed. For this experiment, four different mixture compositions were calculated:

- REF: Reference mixture containing only virgin aggregates
- C-100RA: Mixture containing 100% coarse recycled aggregates. Fines are all virgin aggregates.
- C-75RA: Mixture containing 75 % coarse recycled aggregates and 25 % coarse virgin aggregates. Fines are all virgin aggregates.
- C-50RA: Mixture containing 50 % coarse recycled aggregates and 50 % coarse virgin aggregates. Fines are all virgin aggregates.

The steps for creating the mixture have been used from Copuroğlu [2018]

Scope

Determining the compressive strength of concrete mixtures containing recycled coarse aggregates.

Process

The concrete strength class for the cubes is determined to be C35/45, for a normal concrete mixture. The following steps were performed to determine the compressive strength:

1. Determine material selection
2. Check water cement factor
3. Check cement binder
4. Calculate concrete mixtures
5. Create concrete mixture and perform slump test
6. Preparing, filling and labelling the cubes
7. Perform compressive strength test

A summarized overview of steps 1-4 can be found on the next page (table 5.6), along with the mixture design. A detailed description of the mix-design calculations can be found in appendix E.

Steps

Table 5.6: Steps 1-4

1. Determine material selection			
Water			
CEM III B 42.5N			
Recycled aggregates of the coarse fraction (4-12mm)			
2. Water cement factor			
wcf = $\frac{b}{f_{ck}-a\cdot N_n+c} = \frac{18}{45-(0.75\cdot 51)+30} = 0.49$			
Environmental class XC3:			
Maximum wcf = 0.55			
Minimum cement = 280 kg/m^3			
3. Check cement binder			
Consistency class S3 (plastic behaviour)			
Slump 100-150mm			
Water content 190 l/m^3			
$W_{cement} = \frac{W_{water}}{wcf} = \frac{190}{0.49} = 387.9kg/m^3$			
4. Cement paste overview for 1m^3 concrete			
	Mass (kg)	Density (kg/m^3	Volume (m^3)
Cement	387.9	2950	0.13
Water	190	1000	0.19
Air	-	-	0.01
Total cement	-	-	0.33
Total aggregates	-	-	0.67

Now it is time to create a PSD for this mixture. Using this PSD the mass of each sieve fraction (recycled) aggregate is determined. The design area graph on which the PSD is based on has been retrieved from the minor bend and break (TU Delft, 2018), where a PSD was given for a well behaving mixture. The PSD can be seen on figure 5.6.

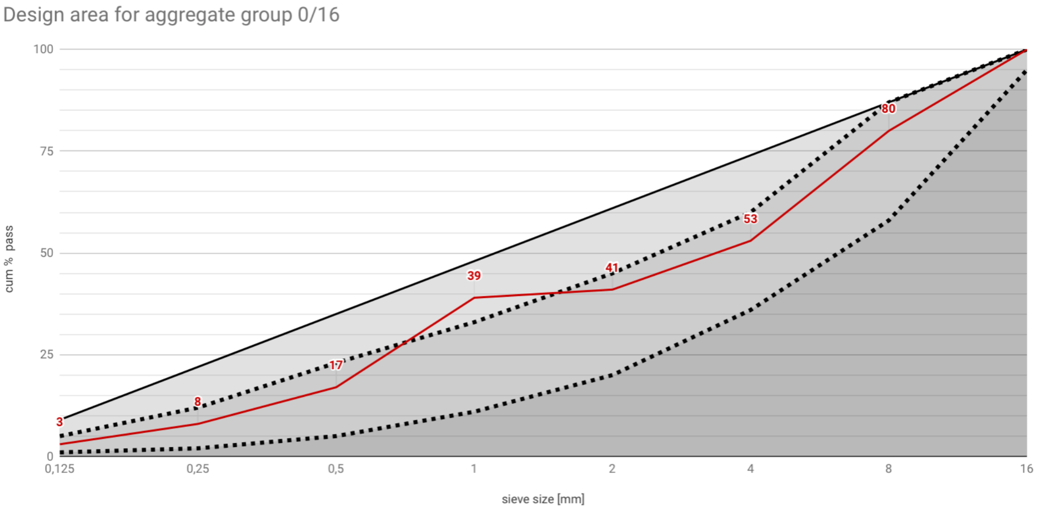


Figure 5.6: PSD for mix design

This PSD can now be transformed for the mass of each sieve fraction (recycled) aggregate that is needed for each of the four different mixtures. The total mix design can be seen in table 5.7 on the next page.

Table 5.7: Concrete mix design

Reference mixture				100% RA mixture			
Cement	15.52kg			Cement	15.52kg		
Water	7.6l			Water	7.6l		
Air	1%			Air	1%		
Cement paste total	0.136m^3			Cement paste total	0.136m^3		
Aggregate total	0.0264m^3			Aggregate total	0.0264m^3		
	Through sieve	Mass VA (kg)	Mass RA (kg)		Through sieve	Mass VA (kg)	Mass RA (kg)
Sand	0.125	1.35	0.00	Sand	0.125	1.35	0.00
	0.25	2.26	0.00		0.25	2.26	0.00
	0.5	3.16	0.00		0.5	3.16	0.00
	1	10.38	0.00		1	10.38	0.00
	2	1.81	0.00		2	1.81	0.00
Gravel	4	5.42	0.00	Gravel	4	0.00	5.42
	8	16.99	0.00		8	0.00	16.99
	16	23.36	0.00		16	0.00	23.36
Total		64.72	0.00			18.95	45.77
75% RA mixture				50% RA mixture			
Cement	15.52kg			Cement	15.52kg		
Water	7.6l			Water	7.6l		
Air	1%			Air	1%		
Cement paste total	0.0136m^3			Cement paste total	0.0136m^3		
Aggregate total	0.0264m^3			Aggregate total	0.0264m^3		
	Through sieve	Mass VA (kg)	Mass RA (kg)		Through sieve	Mass VA (kg)	Mass RA (kg)
Sand	0.125	1.35	0.00	Sand	0.125	1.35	0.00
	0.25	2.26	0.00		0.25	2.26	0.00
	0.5	3.16	0.00		0.5	3.16	0.00
	1	10.38	0.00		1	10.38	0.00
	2	1.81	0.00		2	1.81	0.00
Gravel	4	1.36	4.06		4	2.71	2.71
	8	4.25	12.74		8	8.50	8.50
	16	5.84	17.75		16	11.68	11.68
Total		30.41	34.34	Total		41.85	22.87

A summarized overview of steps 5-7 can be found in table 5.8. A detailed description of these steps can also be found in appendix E.

Table 5.8: Steps 5-7

5. Create concrete mixture and perform slump test
1. Put all aggregates inside mixing device
2. Add 70% of the water
3. Mix for 30 seconds
4. Wait 15 minutes for water absorption by the aggregates
5. Add cement and mix for 3 minutes
6. Whilst mixing, add the rest of the water
7. Stop the mixer
8. Perform slump test
6. Preparing, filling and labelling the cubes
1. Oil the cubes
2. Fill the cubes for 60% and vibrate for 30 seconds
3. Overfill cubes and vibrate for 30 seconds
4. Add label
5. Add plastic cover
6. Put the cubes inside the climate chamber
7. De-mould the cubes after 1 day
7. Perform compressive strength test
1. Put concrete cube in testing device, with the label pointed towards the person
2. Turn on machine and let the test run
3. After the test is done, get the cubes out and note the results
4. Clean the testing device
5. Repeat steps 1-4 for each cube

There are three tests for compressive strength in total (after 2, 7 and 28 days) and each test requires 3 cubes of each mixture. In total, 12 cubes were used for each test.

Figure and table

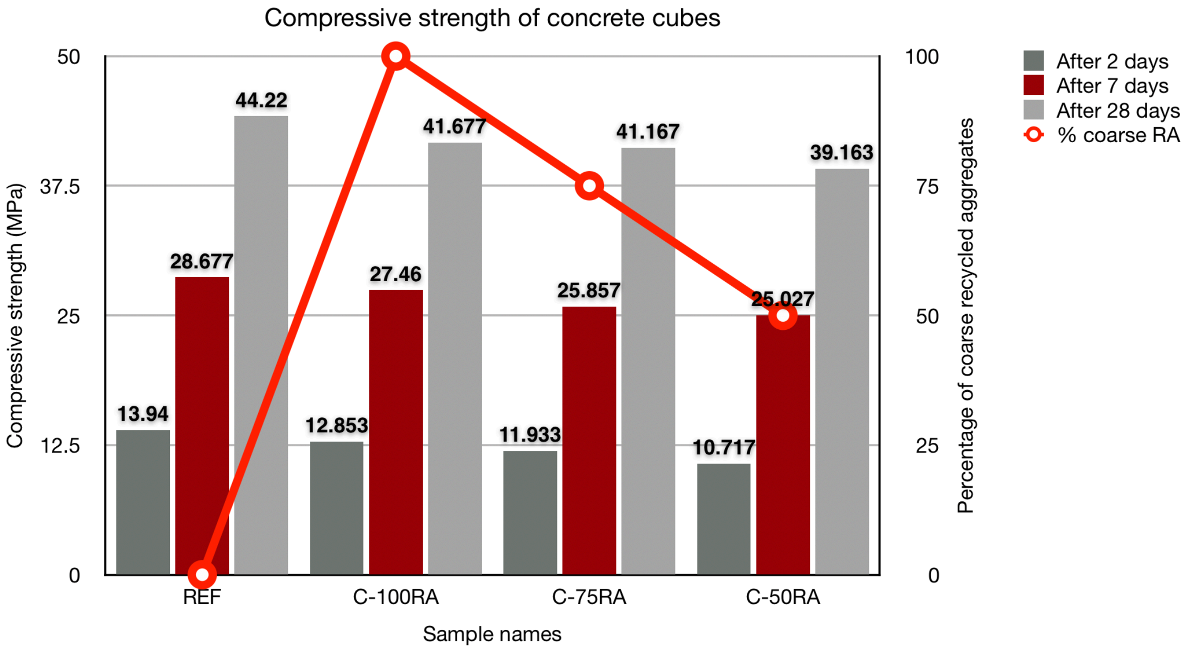


Figure 5.7: Compressive strength test results

Table 5.9: Compressive strength concrete cubes

Compressive strength after:	2 days (MPa)	7 days (MPa)	28 days (MPa)
REF average	13.94 ± 0.22	28.68 ± 0.32	44.22 ± 1.18
C-100RA average	12.85 ± 0.32	27.46 ± 0.51	41.68 ± 1.71
C-75RA average	11.93 ± 0.25	25.86 ± 0.48	41.17 ± 0.64
C-50RA average	10.72 ± 0.07	25.03 ± 0.12	39.16 ± 1.88

Explanation

Detailed results can be found in appendix E.

The specimens with recycled aggregates are expected to perform a little less compared to the reference mixture in terms of compressive strength. This is most likely due to the additional water absorption that the recycled aggregates have. Higher water absorption means that more water is needed to compensate for these effects. However, for this experiment, only the amount of recycled coarse aggregates has been changed and the amount of water used for each mixture is constant.

As can be seen, the compressive strength of the specimens containing coarse recycled aggregates perform less well compared to the reference mixture. However, it seems that the mixture containing 100 % coarse recycled aggregates performs better then the mixtures containing 75- and 50% coarse recycled aggregates. This is an unexpected outcome, since more recycled aggregates in a mixture would mean more water absorption. More water absorption means that the effective water-to-cement factor will decrease, changing the properties of the mixture. A possible explanation for the better performance of the 100 % coarse recycled aggregate cubes compared to the 75 % and 50 % cubes could come from grain interlocking. According to Neville [2002] smooth coarse aggregates lead to a lower compressive strength, typically by 10 per cent, than when roughened.

Possible origins of the lower compressive strength of the C-75RA and C-50RA mixtures could also be explained by observations during the concrete casting. For the C-75RA mixture, one liter of water was added to the mixture for the slump to be conform the norms, since the mixture would not slump the first time. More water can have implications on the compressive strength since the wcf will increase with possible decrease of compressive strength as a result. The C-50RA also showed around 30mm less slump compared to the other mixtures, creating doubts on the composition of this mixture. Also, bleeding was observed for both the C-75RA and C-50RA cubes. As said, bleeding is caused by aggregates that are not able to hold the mixing water when they settle down and can be prevented by, for example, reducing water content or vibration time. Since more water was added, the bleeding observation seems logical with less compressive strength performance as a plausible result.

Another factor that has influence of concrete compressive strength is the aggregate-cement paste interface. This has to do with the ITZ. As for using RA instead of VA, RA have some hydrated cement on the surface. When the new cement paste gets around both the aggregate and the hydrated cement, more interface transition zones occur, resulting in a higher chance of failure in the cube to compressive strength. Since the RA show less compressive strength, this seems like a plausible explanation.

Conclusion

Not accounting for the additional water absorption when making a concrete mixture conform the norm has got negative results in terms of compressive strength. The compressive strength of specimens containing recycled coarse aggregates perform slightly less compared to the reference mixture which contains VA only. Besides water absorption, the bleeding that was observed for the C-75RA and C-50RA specimens could be another reason for worse compressive strength performance. Higher chances of failure in the RA cubes due to more interfacial transition zones should be taken into account. However, the RA prove to have good grain interlocking which raises compressive strength. Taking these factors into account, recycled aggregates should be able to perform better and thus be a good replacement for a new concrete mixture.

5.2. Examination of milling method for liberating cement paste

Cement has got a very vital role in terms of usage in concrete and emission of CO_2 in the environment. Therefore, liberation of cement paste from recycled aggregate particles could increase the amount of cement that can be recoverd during the recycling process. This final paragraph describes the possibilities of liberating cement paste from recycled aggregates. §5.2.1 starts with a method called "milling" where a laboratory modified milling test along with results are given. §5.2.2 describes two tests, namely the XRF and XRD respectively, which tell if cement is actually liberated by milling or not.

5.2.1. Milling aggregates

Method

Milling is a method for liberating cement from recycled aggregates in a laboratory modified milling machine. The machine looks like a scaled down version of the Los Angeles abrasion test. With this test, interaction between steel balls and fine aggregates in size range 0-4mm from the HAS output takes place in a rotating drum. For milling, the output that remains in the pan (<0.063mm) is the most important. This fraction should contain as much cement as possible.

Process

The milling experiment has got the following process:

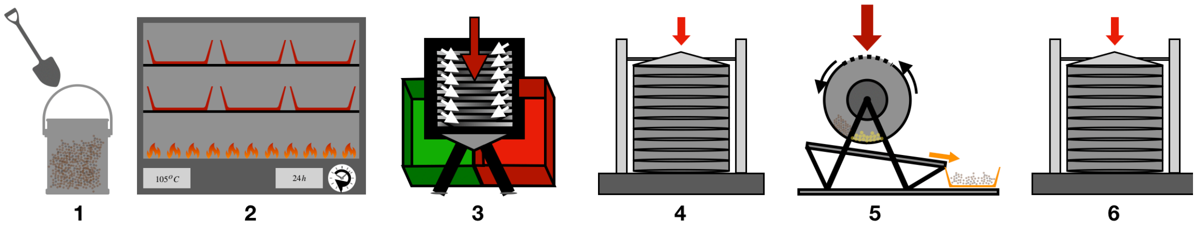


Figure 5.8: Milling steps

1. Create a 5kg representative sample of fine particles in size 0-4mm (On figure 5.8 step 1-3: Only splitting is necessary, since the material is already dry because of the HAS
2. Sieve one sample as reference sample (On figure 5.8 step 4)
3. Weigh 15kg of steel balls size 10mm, for a mass ratio of 1:3
4. Put both the steel balls and sample in the milling device (On figure 5.8 step 5)
5. Mill for a pre-described amount of time (here: 3, 5, 7 and 10 minutes)
6. Empty the mill and collect all materials
7. Sieve materials on the 8mm sieve, so the steel balls are removed from the sample
8. Sieve the sample and weigh each fraction (On figure 5.8 step 6)
9. Create two samples of material in the pan (<0.063mm), for the XRF and XRD
10. Create a PSD

Table and figures

The sample name is built up from the test with the rotation time, so Mil-0 means a milling sample that has rotated for 0 minutes.

Results

As can be seen, the samples that have been milled for 5 and 10 minutes show the highest weight percentage of material below 0.063mm with a value of 3.73% and 4.07% respectively. When only looking at milling results, it seems that a milling time of 5 or 10 minutes is the best for liberating cement. However, prove is needed for the amount of cement that is actually

Table 5.10: Milling results

Sample name	Milling time (minutes)	wt% <0.063mm
Mil-0	0	2.02
Mil-3	3	2.91
Mil-5	5	3.73
Mil-7	7	2.67
Mil-10	10	4.07

in those samples, since the goal of milling is to liberate cement from the aggregates. This is investigated using XRF and XRD tests, which are discussed in §5.2.2. The outcome of those tests provide information about the most efficient way to liberate cement using milling.

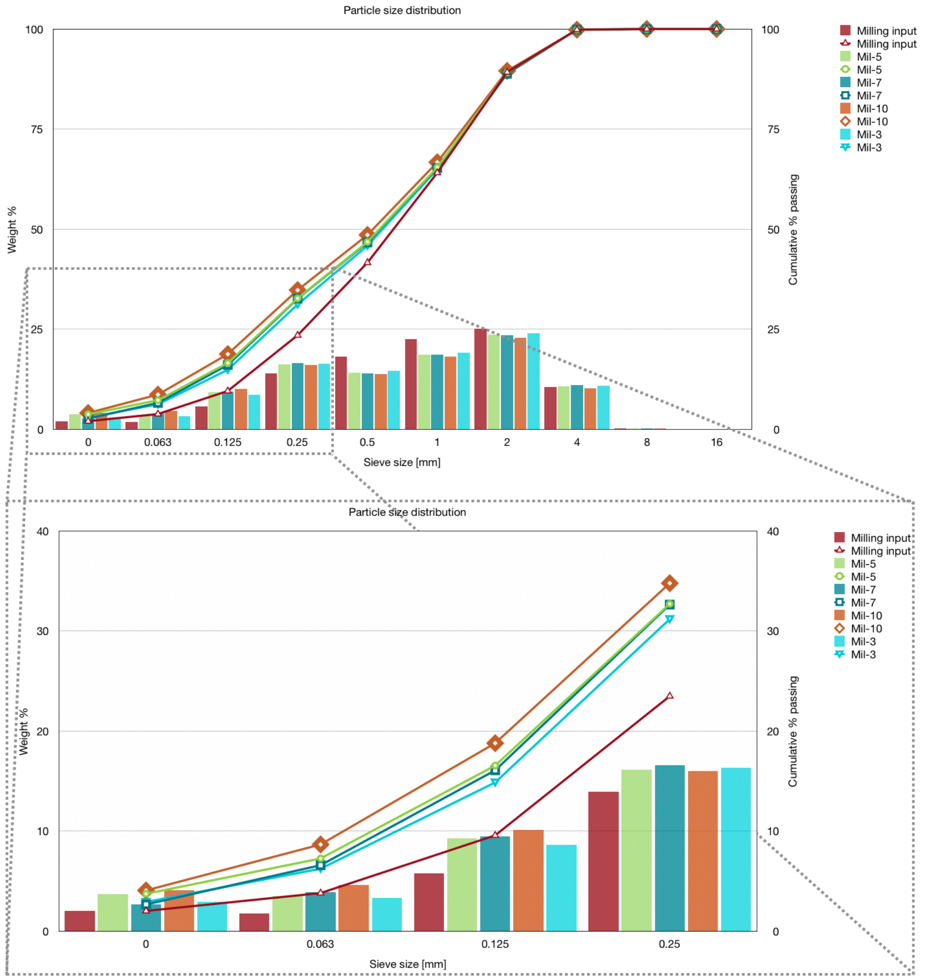


Figure 5.9: PSD of milling

5.2.2. X-ray fluorescence (XRF) and X-ray diffraction (XRD)

Method

XRF and XRD are analytical methods to determine elemental composition of materials and the phase composition [Masone, 2015]. Both methods prove to be fast, accurate and non-destructive to the used materials whilst needing minimal sample preparation. The combination of XRF and XRD is an excellent solution for routine, on-line process and quality control of clinker phases. For XRF, the important parameters to look at are the amounts of CaO and MgO [Masone, 2015].

Scope

Determining the composition and phase of the milled samples.

Process

Figure 5.10 shows the setup for the XRF and XRD. A picture of a real XRD can be seen in figure F.3 in appendix F

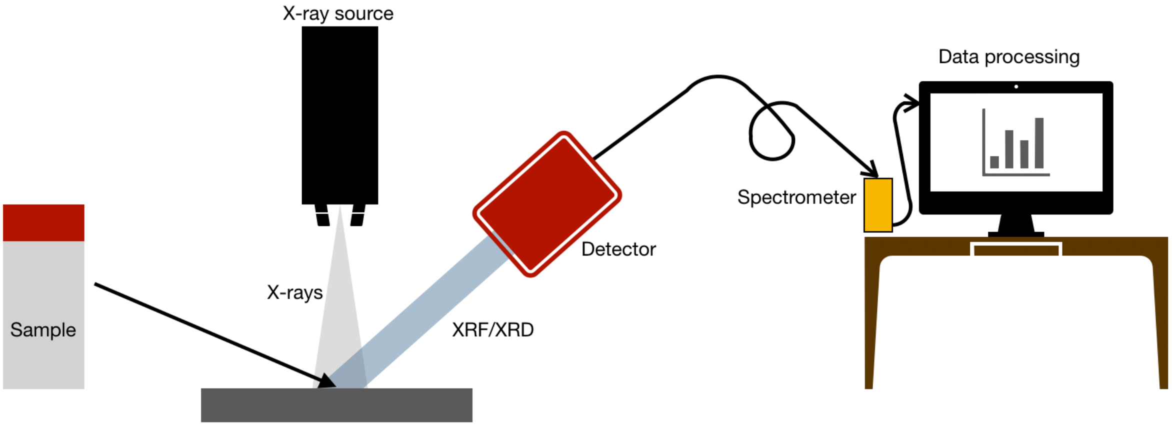


Figure 5.10: XRF and XRD test setup

The experiment has got the following process:

1. Put sample in the XRF/XRD
2. XRF/XRD will start. X-rays strike the material where some are absorbed and some pass through
3. Spectrometer converts the data
4. Computer processing results in quantitative data about the composition of the sample

Figures and tables

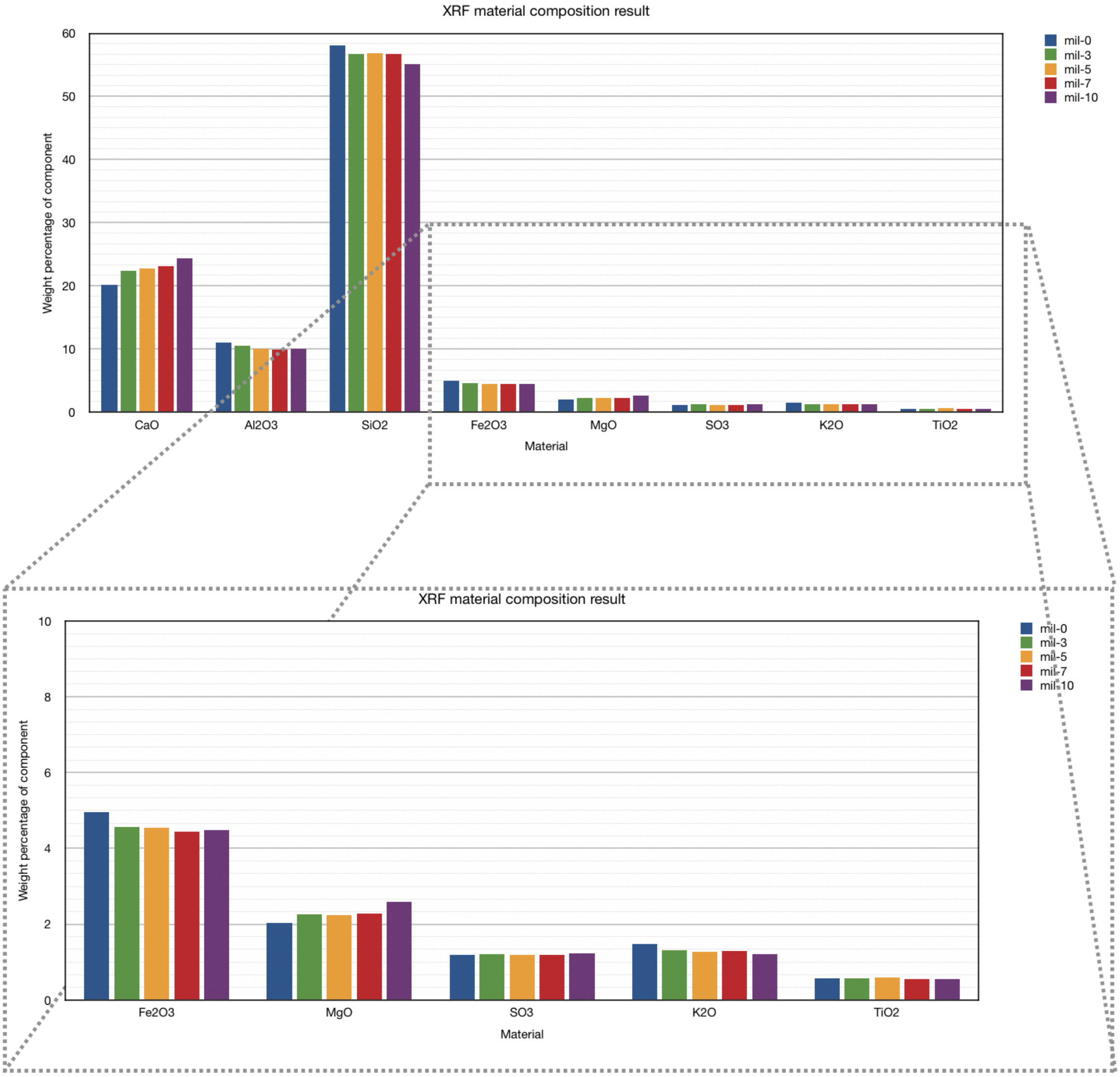


Figure 5.11: XRF results

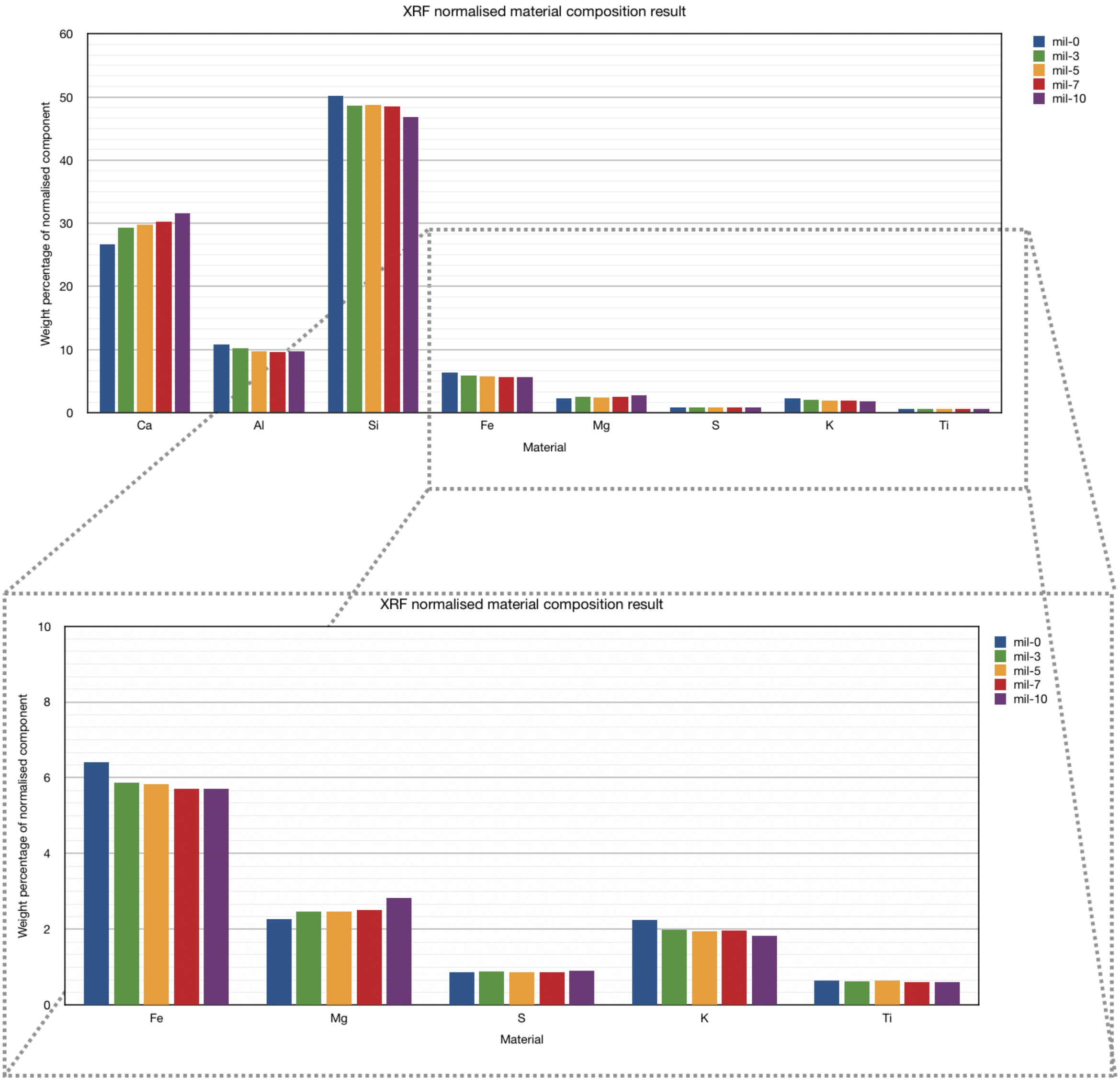


Figure 5.12: XRF normalised results

Table 5.11: XRD quantities

Compound	Mil-0 wt%	Mil-5 wt%	Mil-10 wt%
C_2S	0.0080	0.0015	0.0035
CSH	0.0085	0.0197	0.0019
AL_2O_3	0.0118	0.0159	0.0159
Ettringite	0.0100	0.0036	0.0118
Muscovite	0.0571	0.0548	0.0556
SiO_2	0.7142	0.7101	0.6766
Portlandite	0.0027	0.0025	0.0019
$CaAl_2O_4$	0.0590	0.0450	0.0414
Calcite	0.0920	0.1195	0.1455
Dolomite	0.0118	0.0080	0.0189
Wollastonite	0.0110	0.0193	0.0153

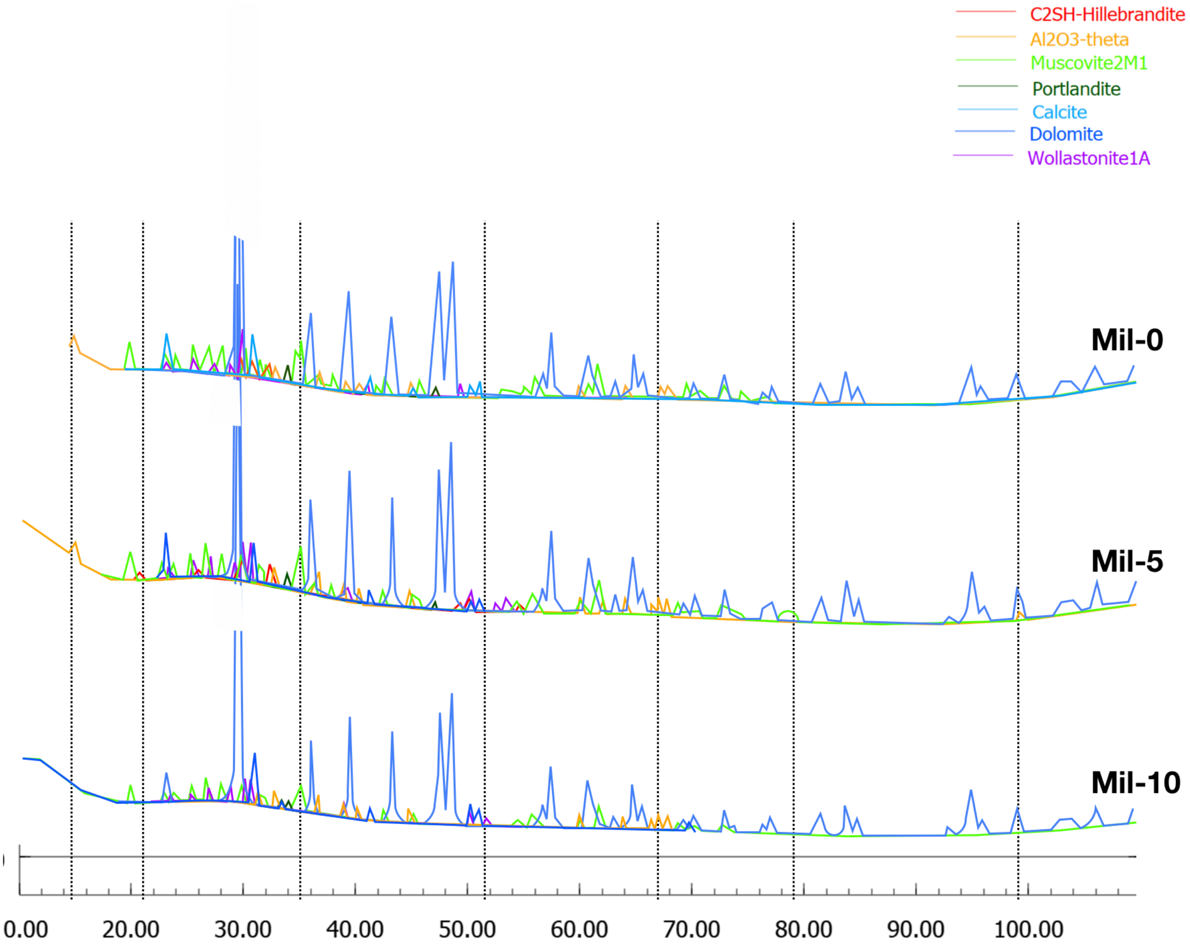


Figure 5.13: XRD graphical results

Result

XRF

The XRF data shows an initial weight percentage of 20.15% and 2.04% of CaO and MgO respectively (figure 5.11). This increases to a maximum value at 10 minutes of milling with 24.31% for CaO and 2.59% for MgO. When the results are normalised by recalculating the composition of materials excluding oxygen, the graph shows an initial weight percentage of 26.61% and 2.26% of Ca and Mg respectively (figure 5.12). This increases to a maximum value at 10 minutes of milling with 31.62% for Ca and 2.83% for Mg.

XRD

The XRD shows very little difference in the peaks when comparing mil-0, mil-5 and mil-10. The only observable differences are indicated by the dotted vertical lines. These dotted lines can indicate a difference in peak height at that point or (un)visible peaks compared to the other graphs.

Explanation

XRF

CaO and MgO are the main tracers for the liberated cement. Other materials, like Al_2O_3 and Fe_2O_3 are compounds in cement as well, but only for a minor amount. SiO_2 is a compound that is found in both the aggregates and the cement, so this will not be used as a tracer. What can be seen is that cement is liberated from the aggregates due to the increase in CaO and MgO from the XRF analysis. However, it is not a significant increase. When time versus cement gain is considered, milling for 3 minutes seems to be the most efficient and fastest way to liberate some cement from the aggregates. However, this still is only a 10% increase of cement. For 10 minutes, the increase of cement liberation is 17%.

XRD

The objective of the XRD was to identify C-S-H since this is the main hydration product of portland cement, but since this compound has got a varying composition and amorphous nature C-S-H was not identified by the XRD. Both figure 5.13 and table 5.11 also show no significant change in phases between the samples. However, there are traces of hydration products like portlandite and ettringite but only in very minor amounts.

Conclusion

Milling does not seem to be a very good additional step in the recycling chain for liberating cement from the fine output of the HAS. When the HAS output is sieved, around 20.15 wt% is cement. After milling for 10 minutes, this number is increased only to 24.31wt% or 26.62wt% when the results are normalised. So, milling does liberate cement due to the interaction between the steel balls and aggregate, but there is no significant increase in the total cement comparing no milling to 10 minutes of milling looking at only the XRF. The XRD proved not to be efficient in terms of identifying C-S-H and other cement phases. Since milling also consumes both time and energy, the profits of the additional gained cement would be very low.

Conclusion

The report examined how properties of recycled aggregates from construction and demolition waste can be compared to virgin aggregates in order to possibly use them in a new concrete mixture. Both the coarse and the fine aggregate fraction of the ADR and HAS output were examined.

The coarse aggregates show very different properties when compared to virgin aggregates. Their water absorption is very high, their shape is mostly angular whereas virgin aggregates can be both angular and rounded. Water absorption can easily be compensated for. The LA abrasion coefficient is within the limits of the norm. Compressive strength of mixtures with recycled coarse aggregates was lower compared to the reference, but this has to do with the high water absorption which also lowers the wcf. Still, coarse recycled aggregates show good grain interlocking due to their angular shape and an increase in compressive strength once they replaced more virgin aggregates indicating very good potential for them to be used in a new concrete mixture.

The fine aggregates also showed high water absorption, but this is caused by the large surface-to-volume ratio and cement paste attached to the surface of the aggregates as the XRF proved. This can be compensated for and it is not considered as a problem. Using milling in the combination with XRF the amount and composition of cement paste on the fine aggregates was determined. The XRD proved not to be able to detect C-S-H as the main hydration product of portland cement and did not give additional information about the milling outputs.
Milling the fine aggregates to obtain cement paste turned out not to be very efficient. Only a small increase in wt% cement was observed and when time and energy are considered, the profits of the liberated cement would be very low.

Both the fine and coarse recycled aggregates from the ADR and HAS separation products have good properties for both usage and replacement of virgin aggregates in a new concrete mixture. Using or replacing this material in fresh concrete mixtures will decrease the need for new materials, preventing raw material depletion and alleviating the environmental stress of concrete.

Recommendations

This research has shown that recycled aggregates from the ADR and HAS are suitable for using them and replacing virgin aggregates in a new concrete mixture. Still, it is recommended to investigate more properties of these aggregates. Firstly, the water absorption test must be performed more, since it proved to give inconsistent results. Freez-thaw is also an important property, but equipment was not available during this research. The XRD also needs to be investigated more in order to tune it for the right output components.

Performing more different compressive strength tests is advised as well. In this research, only the coarse fraction has been (partially) replaced by recycled aggregates without accounting for the higher water absorption of these aggregates. Examining different mixture compositions (only fine replacement, both fine and coarse replacement, accounting for water absorption and addition of admixtures) results in better insight into the actual properties of recycled aggregates. One of the considerations when making concrete should be to increase the water absorption time for the aggregates.

Also, long term effects, mechanical properties and durability of RA would be of importance for better knowledge about the material. For example determination of water penetration, chloride and sulphate attacks, flexural strength and knowing the source of the recycled aggregates.

A

Sample preparation

In this appendix, the general workflow for creating samples is described. For accurate results, a representative sample is necessary. A representative sample is *"A reflection of the total population of aggregates. This is reached when all 'sub-populations' in the sample have the same ratio compared to the total population."* [Fresco, s.d.] The sample should always have the right amount of particles in it. A too small sample would introduce statistical uncertainty and sampling of an inhomogeneous heap could introduce clusters of specific particles in the sample. The method that will be used for creating samples for all experiments is called splitting. This divides a particulate stream of particles into two equal streams. By splitting earlier splitted fractions, a smaller sample size can be obtained without changing the contents of the heap. [Bakker, 2018]
The splitter that has been used can be seen on figure A.1.

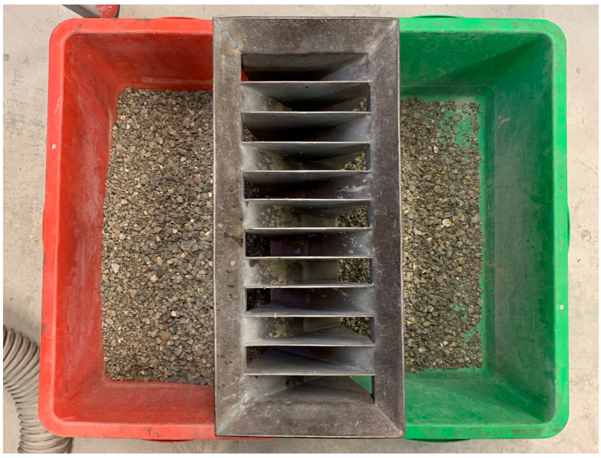


Figure A.1: Splitter

A small example: When a 1kg sample needs to be obtained from a 8kg heap, the following steps are executed:

- Mix the heap
- Split the heap so two heaps of 4kg are left
- Split one of the two 4kg heaps again, so two heaps of 2kg are left
- Split one of the two 2kg heaps again, so two heaps of 1kg are left

After these steps, a representative sample of 1kg is remaining.

B

Particle size distribution

The input data can be seen in the table below, as well as the resulting particle size distribution (PSD) graph for each dataset.

Table B.1: PSD input data

Particle size (mm)	B-ADR mass retained	B-ADR cum. % passed	A-ADR1 mass retained	A-ADR1 cum. % passed	A-ADR2 mass retained	A-ADR2 cum.% passed
16	0	100	0	100	0	100
8	1.3725	100	0.0443	100	1.8071	100
4	1.4766	78.41	0.1196	99.36	3.3959	76.33
2	0.9463	55.18	0.6046	97.64	1.6828	31.85
1	0.6895	40.29	1.4891	88.96	0.5142	9.80
0.5	0.6188	29.45	1.6366	67.55	0.0919	3.07
0.25	0.6473	19.71	1.5797	44.03	0.0369	1.87
0.125	0.4607	9.53	1.1457	21.33	0.0376	1.38
0.063	0.1010	2.28	0.2601	4.87	0.0316	0.89
Pan	0.0441	0.69	0.0785	1.13	0.0363	0.48
Total	6.3568		6.9582		7.6343	

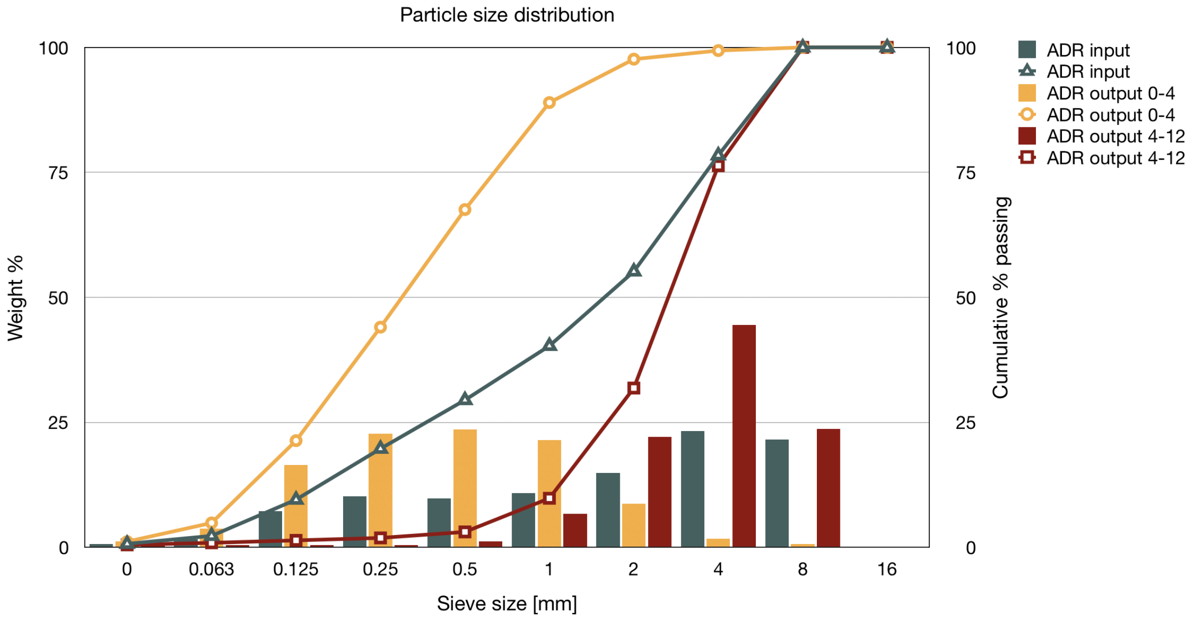


Figure B.1: Particle size distribution graph

C

Specific gravity and water absorption

The results of the two coarse water absorption experiments can be seen in table C.1 below, as well as pictures of the material that has been tested on figure C.1

Table C.1: Water absorption coarse aggregates with standard deviation

Description	**Sample number**			
	CI	**CII**	**CIII**	**CIV**
Weight of sample (g)	1006	1009	1000	1000
Weight of vessel + sample + water (g), A	2452.4	2284.0	2448.0	2300.0
Weight of vessel + water (g), B	1856.3	1699.9	1855.8	1701.2
Weight of saturated & surface dry sample (g), C	1008.3	1009.9	999.4	966.1
Weight of oven dry sample (g), D	958.4	960.8	954.2	922.6
Specific gravity = [D/(C-(A-B))]	2.325	2.256	2.343	2.512
Apparent specific gravity = [D/(D-(A-B))]	2.645	2.551	2.636	2.849
Water absorption in % of dry weight = [(C-D)/D]x100	5.207	5.110	4.737	4.714
Average values	**Specific gravity**	**2.359 ± 0.109**		
	App. specific gravity	**2.439 ± 0.174**		
	Water absorption	**4.942 ± 0.235**		

Figure C.1: Coarse aggregate samples

Fine aggregates

The result of the two fine water absorption experiments can be seen in table C.2 below, as well as pictures of the material that has been tested on figure C.2.

Table C.2: Water absorption fine aggregates with standard deviation

Description	**Sample number**	
	FI	**FII**
Weight of sample (g)	660.0	744.0
Weight of Vessel + Sample + Water (g), A	1676.0	1712.6
Weight of vessel + water (g), B	1303.7	1292.0
Weight of saturated and surface dry sample (g), C	659.4	743.8
Weight of oven dry sample (g), D	601.3	677.4
Specific gravity = [D/(C-(A-B))]	2.094	2.096
Apparent specific gravity = [D/(D-(A-B))]	2.626	2.638
Water absorption, percentage dry weight (%) = [(C-D)/D]x100	9.66	9.80
Average values	**Specific gravity**	2.095 ± 0.001
	App. specific gravity	2.632 ± 0.008
	Water absorption	9.73 ± 0.10

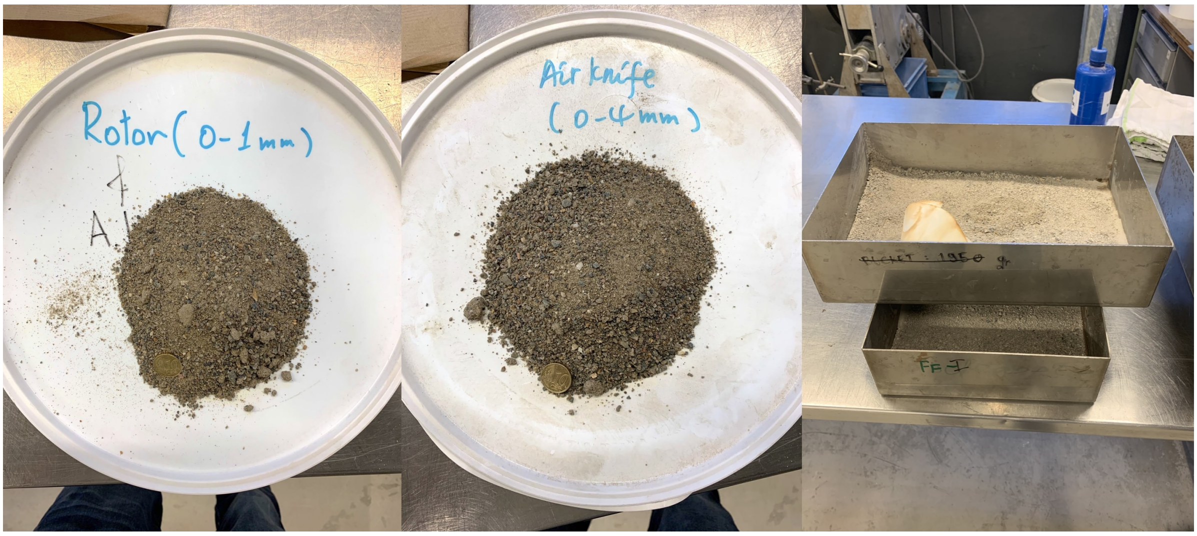


Figure C.2: Fine aggregate samples

D

Los Angeles abrasion

The test results can be seen in table D.1 below.

Table D.1: Los Angeles test results

Sample name	Range classification (mm)	Number of balls	Mass of ball load (g)	Mass before test	Mass after test	Mass retained on 1.6mm sieve	Mass passing 1.6mm sieve	LA coefficient
4-8 I	4 to 8	15	3531.6	5017.4	5012.2	3710.3	1301.9	25.79
4-8 II	4 to 8	15	3531.6	4998.5	4893.8	3673.9	1309.9	26.52
8-11.2 I	8 to 11.2	19	4447.6	5001.2	4995.9	3563.2	1432.7	28.74
8-11.2 II	8 to 11.2	19	4447.6	4999.3	4992.2	3534.9	1457.3	29.30

Table D.2: Los Angeles abrasion loss, references retrieved from Pavement interactive

Experimental results	**LA coefficient**
Coarse fraction [10-14mm] average	27.91 ± 1.97
Fine fraction [4-8mm] average	26.16 ± 0.52

For visualisation of the before and after product of the Los Angeles abrasion test, please look at figure D.1 and D.2 below. It shows the before and after product for coarse sample 8-12 II.

Figure D.1: Before and after product of Los Angeles abrasion test

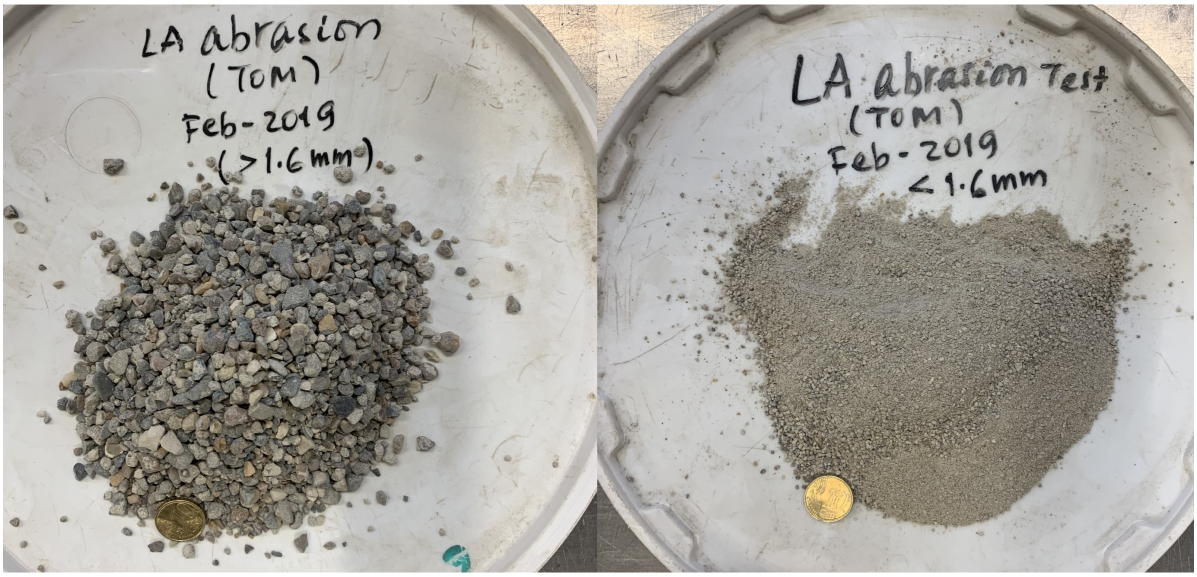


Figure D.2: Sieved material heaps from Los Angeles abrasion test product

E

Concrete mix design

Steps

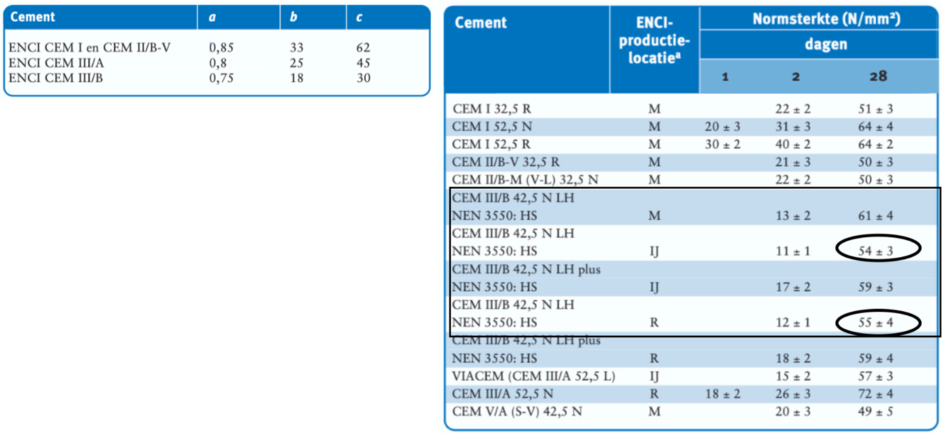
1. Determine material selection

For this concrete mixture, the following materials were used:

- Water
- CEM III B 42.5N
- Recycled aggregates of the coarse fraction (4-12mm)
- Virgin aggregates in sizes 0-16mm

2. Water cement factor

The water cement factor (now referred to as wcf) is an important concrete property. The amount of water has a lot of influence on the compressive strength of the concrete. To determine this wcf, a couple of formulas and the tables from figure E.1 are needed.



Cement	a	b	c
ENCI CEM I en CEM II/B-V	0,85	33	62
ENCI CEM III/A	0,8	25	45
ENCI CEM III/B	0,75	18	30

Cement	ENCI-productie-locatie[a]	Normsterkte (N/mm^2)		
		dagen		
		1	2	28
CEM I 32,5 R	M		22 ± 2	51 ± 3
CEM I 52,5 N	M	20 ± 3	31 ± 3	64 ± 4
CEM I 52,5 R	M	30 ± 2	40 ± 2	64 ± 2
CEM II/B-V 32,5 R	M		21 ± 3	50 ± 3
CEM II/B-M (V-L) 32,5 N	M		22 ± 2	50 ± 3
CEM III/B 42,5 N LH NEN 3550: HS	M		13 ± 2	61 ± 4
CEM III/B 42,5 N LH NEN 3550: HS	IJ		11 ± 1	54 ± 3
CEM III/B 42,5 N LH plus NEN 3550: HS	IJ		17 ± 2	59 ± 3
CEM III/B 42,5 N LH NEN 3550: HS	R		12 ± 1	55 ± 4
CEM III/B 42,5 N LH plus NEN 3550: HS	R		18 ± 2	59 ± 4
VIACEM (CEM III/A 52,5 L)	IJ		15 ± 2	57 ± 3
CEM III/A 52,5 N	R	18 ± 2	26 ± 3	72 ± 4
CEM V/A (S-V) 42,5 N	M		20 ± 3	49 ± 5

Figure E.1: Norm factors for mix design

The wcf can be derived from the following formula:

$$f_{ck} = a \cdot N_n + \frac{b}{wcf} - c \rightarrow wcf = \frac{b}{f_{ck} - a \cdot N_n + c} \tag{E.1}$$

where:

a = 0.75 [constant]
b = 18 [constant]
c = 30 [constant]
N_n = 51 N/mm^2 [Cement strength after 28 days]
f_{ck} = 45 N/mm^2 [Cube strength after 28 days]

Combining the data results in:

$$wcf = \frac{18}{45 - (0.75 \cdot 51) + 30} = 0.49 \tag{E.2}$$

This wcf has been checked and is conform with the environmental class of the concrete mixture, since some maximum values are described in that norm. Since the mixture will be tested in a medium moist area, the chosen environmental class for this concrete is class XC3. Environmental class XC3 states the following:

- Maximum wcf = 0.55
- Minimum amount of cement binder = 280kg/m^3

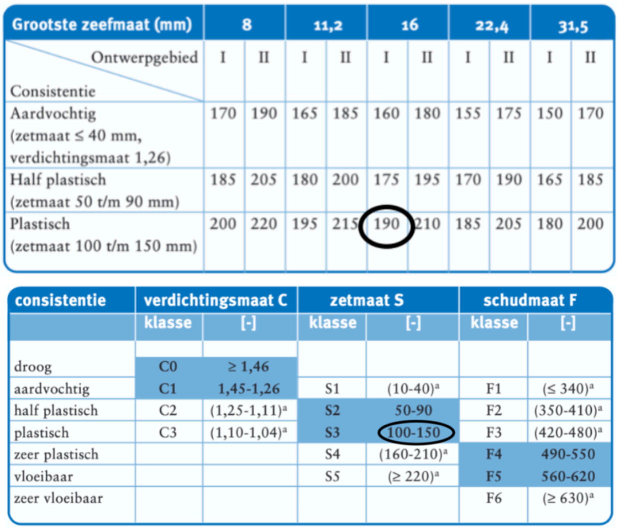
Thus, the wcf is conforming with the norm, but the minimum amount of cement binder needs to be checked.

3. Check cement binder

Since the wcf is known, it is therefore logical to determine the amount of water that is needed, and then calculating the amount of cement via the wcf to check the minimum amount of cement binder.

The amount of water needed is described by the setting of the mixture. The mixture is calculated to be a plastic behaving mixture. This means that the slump should be between 100 and 150mm. Therefore it falls in consistency class S3.

Knowing the state of the mixture (plastic) the effective need for water in the concrete mixture can be seen in the tables in figure E.2.



Grootste zeefmaat (mm)	8		11,2		16		22,4		31,5	
Ontwerpgebied / Consistentie	I	II	I	II	I	II	I	II	I	II
Aardvochtig (zetmaat ≤ 40 mm, verdichtingsmaat 1,26)	170	190	165	185	160	180	155	175	150	170
Half plastisch (zetmaat 50 t/m 90 mm)	185	205	180	200	175	195	170	190	165	185
Plastisch (zetmaat 100 t/m 150 mm)	200	220	195	215	190	210	185	205	180	200

consistentie	verdichtingsmaat C		zetmaat S		schudmaat F	
	klasse	[-]	klasse	[-]	klasse	[-]
droog	C0	≥ 1,46				
aardvochtig	C1	1,45-1,26	S1	(10-40)[a]	F1	(≤ 340)[a]
half plastisch	C2	(1,25-1,11)[a]	S2	50-90	F2	(350-410)[a]
plastisch	C3	(1,10-1,04)[a]	S3	100-150	F3	(420-480)[a]
zeer plastisch			S4	(160-210)[a]	F4	490-550
vloeibaar			S5	(≥ 220)[a]	F5	560-620
zeer vloeibaar					F6	(≥ 630)[a]

Figure E.2: Norm factors for mix design

Known values are the maximum sieve size of 16mm and plastic behaviour. Also, the mixture is designed in design area 1.
According to figure E.2, the minimum amount of water, is 190l/m^3. The definition of the wcf is that it describes the ratio of the mass of water divided by the mass of cement. Since the mass of the water in the mixture is known (190kg/m^3), the amount of cement is easily obtained via:

$$W_{cement} = \frac{W_{water}}{wcf} = \frac{190kg}{0.49} = 387.9kg/m^3 \tag{E.3}$$

with:

W_{cement} = Weight of cement [387.9kg/m^3]
W_{water} = Weight of water [190kg/m^3]
wcf = Water cement factor [0.49]

So, the mass of the cement in this mixture is $387.9kg/m^3$. This is more than the minimum described by the norm for environmental class XC3, so the amount of cement is correct.

4. Cement paste overview
All factors are now known for the cement paste. Below, a brief overview for the cement paste is given. All amounts are described for a mixture of $1m^3$
Now, the different types of mixtures need to be calculated. In total, four different mixtures will be created, namely:

- Reference
- 100 % RA
- 75 % RA
- 50 % RA

For calculating this, a mixture with size $1m^3$ is used for an easy calculation. The contents of the cement paste are already known and are shown in table E.1 After calculating a concrete mixture, the mixture can be made. The steps for making a concrete mixture, storing it and testing its compressive strength will be described on the next pages.

Table E.1: Cement paste overview

	Mass (kg)	Density (kg/m^3)	Volume (m^3)
Cement	387.9	2950	0.13
Water	190	1000	0.19
Air	-	-	0.01
Total cement paste	-	-	0.33
Total aggregates	-	-	0.67

5. Create concrete mixture and perform slump test

Before starting to make a concrete mixture, it is important to first get the materials ready. As can be seen in figure E.3 on the left, different buckets of materials for one mixture have been collected. Once the materials were collected, the following steps were executed:

1. Put all aggregates inside of mixing device
2. Add 70% of the water
3. Mix for 30 seconds (figure E.3, middle)
4. Wait 15 minutes for the water to be absorbed by the aggregates
5. Add the cement and start mixing for 3 minutes
6. Whilst mixing, slowly add the rest of the water
7. Stop the mixer

After these steps, it is time to perform a slump test. As said in chapter 4, a slump test explains the ease with which the concrete flows during placement. According to the mix design, the slump should be between 100 and 150mm. Looking at figure E.3, right, it can be seen that the slump for one of the mixtures was 101mm, which is conform the calculation. After this check, it is time for the next step.

Figure E.3: Material selection (left), mixing (middle) and slump test (right)

6. Preparing, filling and labelling the cubes

Now that the concrete has been made, it is time to put it in the cubes. Before putting the mixture in the cubes, the cubes need to be oiled for easy de-moulding and prevention of the concrete sticking to the cube itself. The oiled cubes can be seen in E.4, left. After oiling, the cubes were filled for about 60 %, and then put on the vibration table for 30 seconds. After that, the cubes were over-filled with concrete and put on the vibration table again, as can be seen in E.4, middle. Now, the cubes need to be labelled and plastic has to be put on top, to prevent water evaporation. This can be seen in E.4, right. The only thing that remains is to put the cubes inside a moist chamber with constant climate for the best possible result. The cubes were de-moulded after 1 day, and were then put to rest in the climate chamber. After resting, it is time for the compressive strength tests.

Figure E.4: Oiled cubes (left), vibration table (middle) and labelling (right)

7. Perform compressive strength test

After the cubes have been filled with concrete, labelled and stored it is time to get them out once it is time for the compressive strength test. For visualisation, the concrete cubes that were tested after 7 days of rest can be seen in figure E.5, left. The testing device can be seen in figure E.5, right. Both the steps for testing and the results can be found below.

Figure E.5: To be tested cubes (left) and testing device (right)

The following steps were performed for testing:

1. Put the concrete cube in the testing device, with the label pointed towards the person
2. Turn on the machine and let the test run
3. After the test has been done, get the cube out and note results
4. Clean the testing device
5. Repeat previous steps for each cube

Table E.2: Compressive strength cubes detailed

Compressive strength after:	2 days (MPa)	7 days (MPa)	28 days (MPa)
REF I	13.88	28.64	42.98
REF II	13.76	28.38	44.36
REF III	14.18	29.01	45.32
RA100 I	12.58	27.69	40.13
RA100 II	12.78	27.81	43.51
RA100 III	13.20	26.88	41.39
RA75 I	12.09	26.25	41.06
RA75 II	11.64	25.32	41.85
RA75 III	12.07	26.00	40.59
RA50 I	10.69	24.96	40.88
RA50 II	10.66	25.16	39.46
RA50 III	10.80	24.96	37.15

F

Figures

Figure F.1: ADR legend

Figure F.2: HAS legend

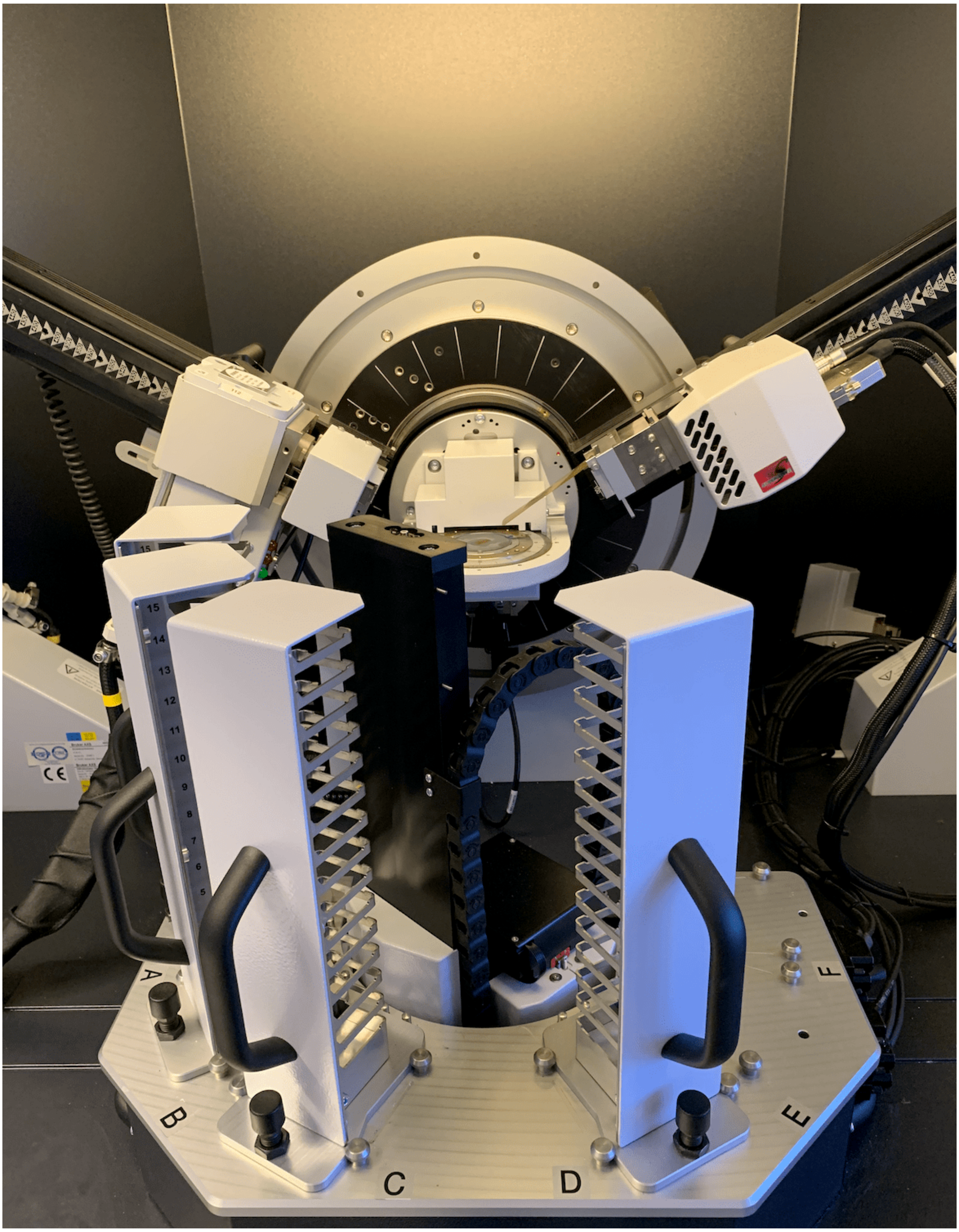


Figure F.3: XRD setup

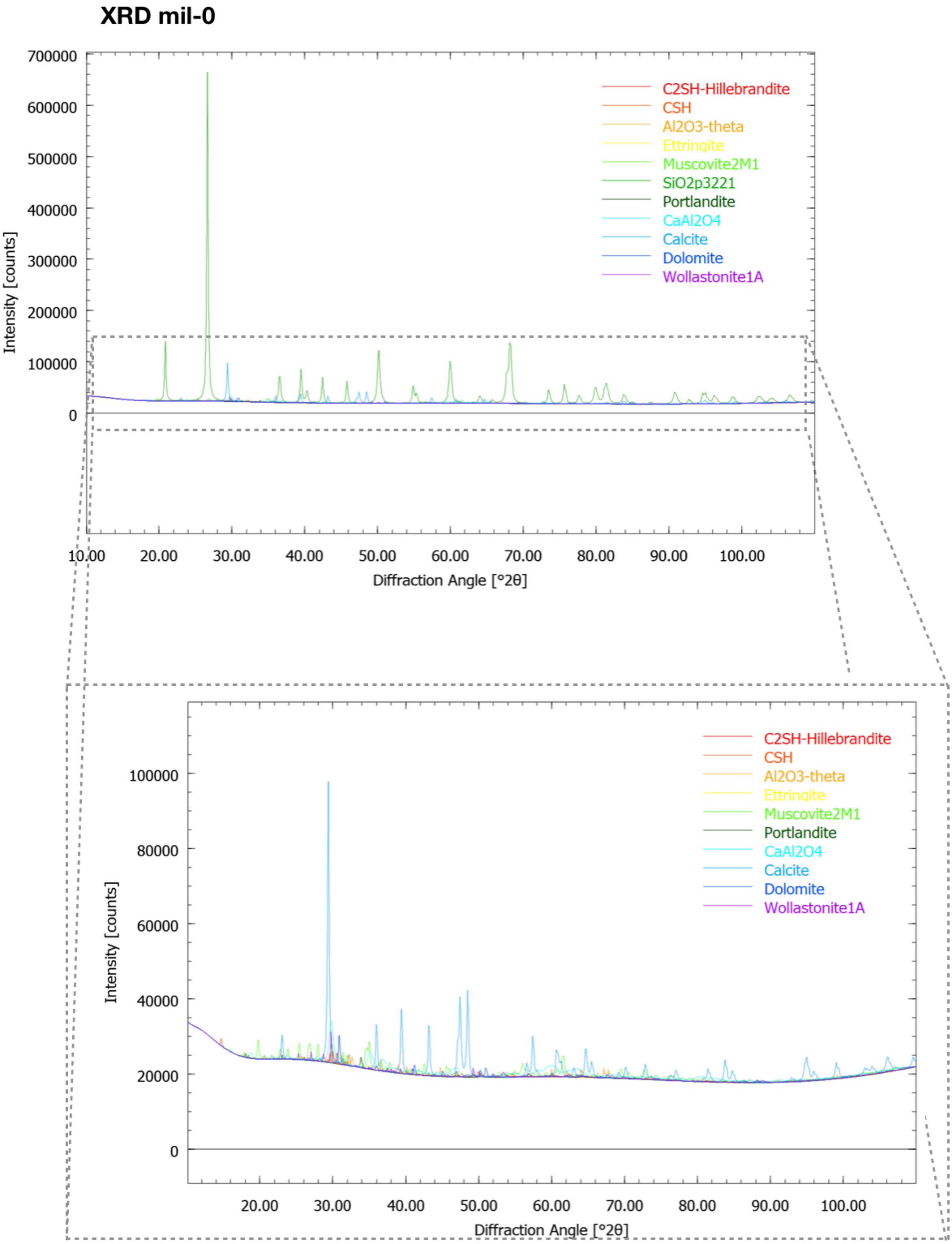


Figure F.4: Mil-0 XRD chart [1/3]

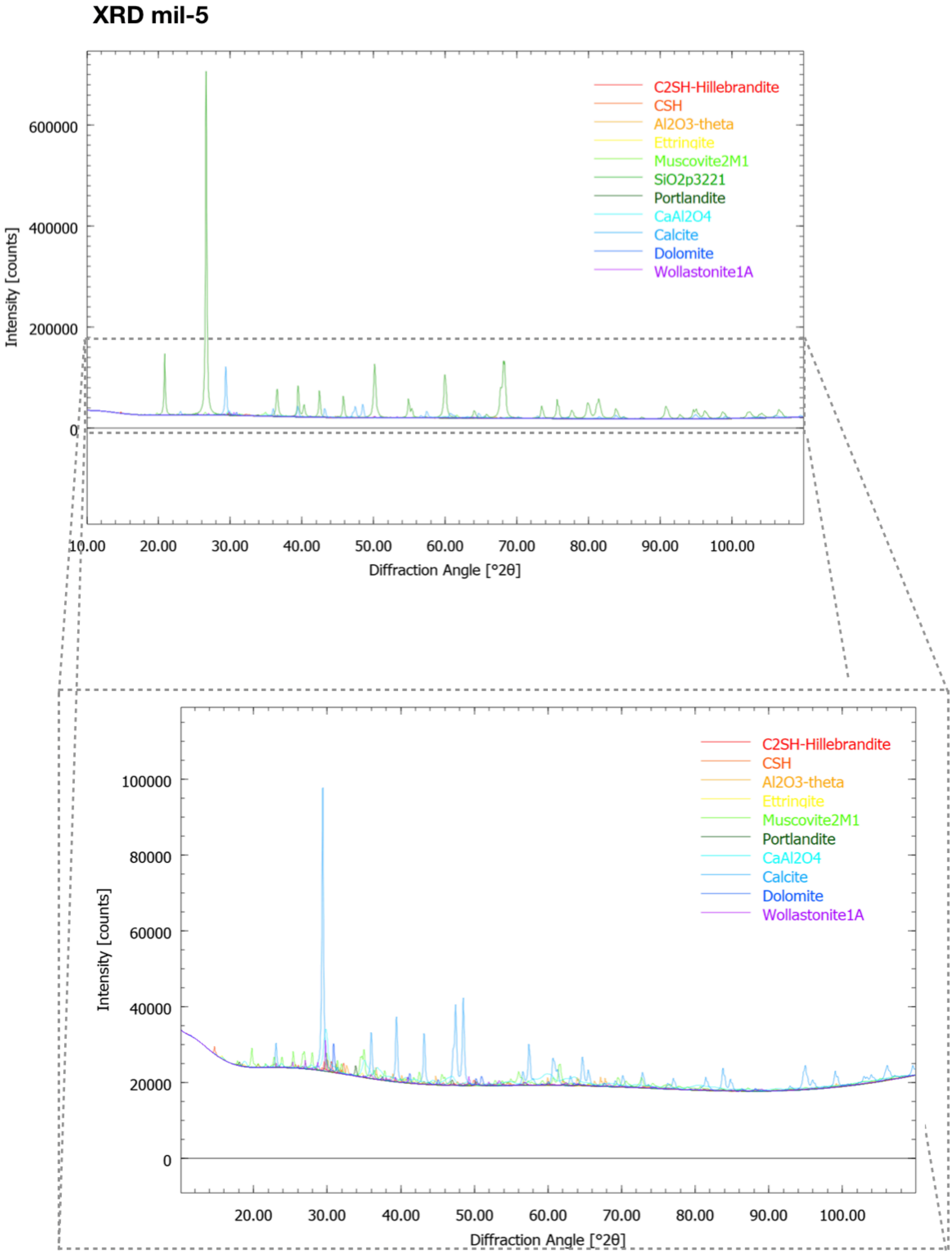


Figure F.5: Mil-5 XRD chart [2/3]

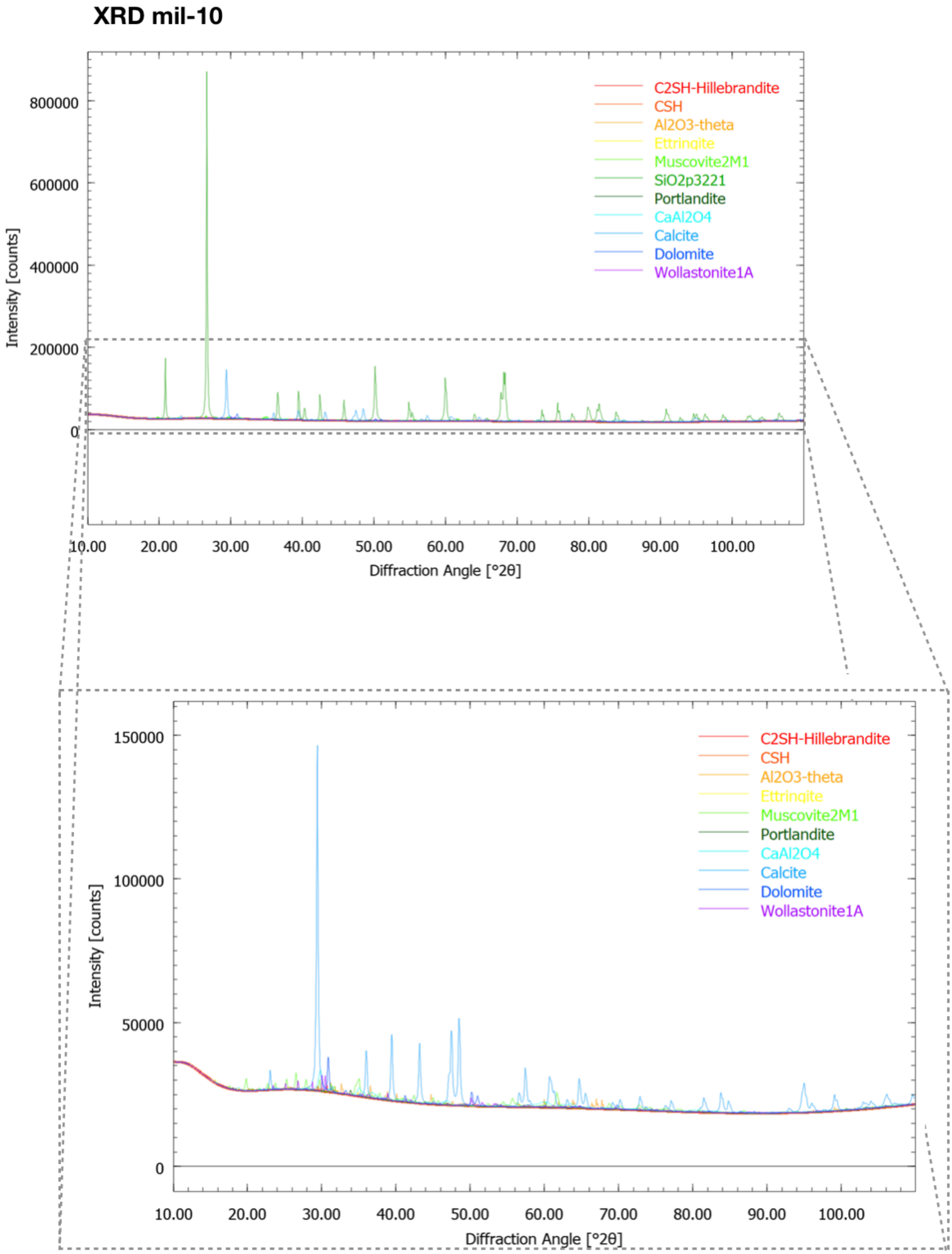


Figure F.6: Mil-10 XRD chart [3/3]

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