Unlocking fRCA Potential: Mortar Testing & Optimization

Exploring the Impact of Fine Recycled Concrete Aggregates (fRCA) on Mortar Mix Strength

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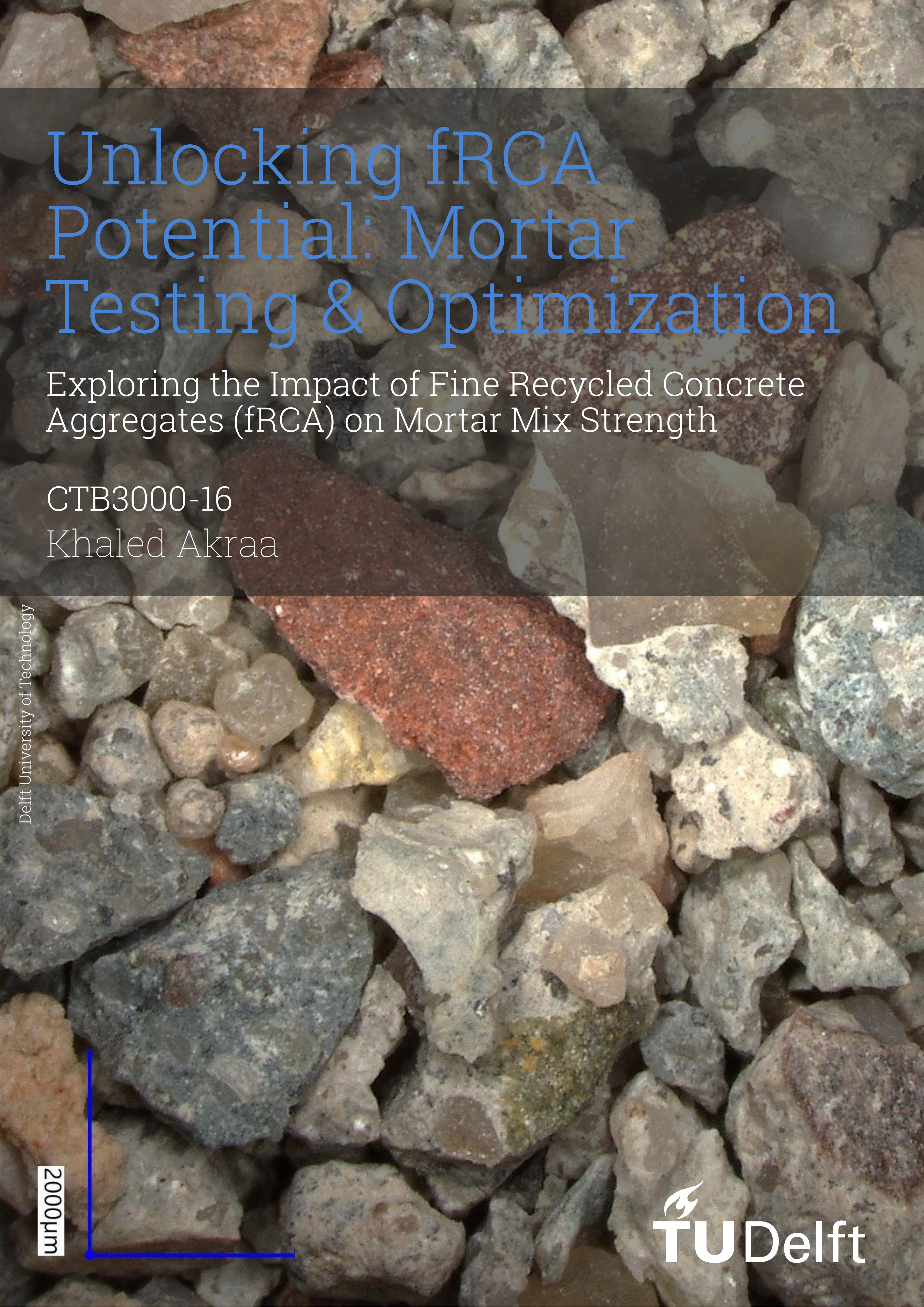

BSC Thesis Unlocking fRCA Potential: Mortar Testing & Optimization

Exploring the Impact of Fine Recycled Concrete Aggregates (fRCA) on Mortar Mix Strength

by

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Cover: Milled fRCA

TU Delft

Preface

I present this bachelor's final project with proud, which is the result of dedicated research and in-depth analysis in the fields of civil engineering, material science, and sustainability. This research addresses a relevant and pressing question within today's construction industry: “What is the best way to improve the properties of fRCA and use it in concrete mixes for civil engineering applications?”

This inquiry reflects the growing emphasis on sustainability and environmental awareness in the construction sector, where recycled concrete aggregate emerges as a promising solution. The use of fRCA not only offers the opportunity to reduce waste but also contributes to a reduction in CO2 emissions by diminishing the demand for natural resources and is helping replace the scarce natural sand.

I conducted a literature review to explore existing knowledge on fRCA and concrete technology. Additionally, I carried out experimental research to develop innovative methods for enhancing the properties of fRCA and making it suitable for a wide range of civil engineering applications.

This project would not have been possible without the unwavering support and guidance of my instructors A. T. Gebremariam and M. Bakker, who encouraged me to think critically and devise creative solutions to complex challenges. Also many thanks to T. Blom and R. Penners for supervising me in the lab.

This final project represents just the beginning of a journey towards a more sustainable future for the construction industry with more fRCA use. I hope that the findings and recommendations in this research contribute to the ongoing development of innovative and sustainable solutions in civil engineering.

I cordially invite you to read and share this report as I aspire to transform the construction industry into a more environmentally friendly and sustainable sector.

Warm regards,
Khaled Akraa
TU Delft
03/11/2023

Abstract

The increasing demand for sand in the construction sector underscores the need for sustainable alternatives to natural sand. This bachelor's thesis explores the application of Fine Recycled Concrete Aggregate (fRCA) produced by Heating air and classification system (HAS) from the Concrete To Cement and Aggregate (C2CA) technology as a sustainable substitute for natural sand. fRCA consists of pure sand and cementitious material, with the removal of extraneous substances such as timber and steel. While fRCA finds applications in various sectors, the challenges in its use in mortar include property variations, cost considerations, and the absence of quality control standards. Addressing these challenges would be crucial for the wider adoption of fRCA in mortar applications.

This research aims to characterize fRCA properties, enhance fRCA quality through acid treatment and milling, determine optimal milling parameters, investigate the influence of the water-cement (W/C) ratio on mortar workability, and assess the compressive and tensile strength of mortar with fRCA. The central inquiry pertains to identifying the optimal approach for enhancing fRCA properties and integrating it into concrete mixes for civil engineering applications.

The study is exploring the effects of untreated fRCA, milled fRCA, and acid-washed fRCA on mortar properties. It is also determined the ideal quantity of milled fRCA to replace natural sand in mortar mixtures. The theoretical evaluation of sustainability in mortar mixes utilizing this specific fRCA have been conducted. This research did not investigate the chemical properties of fRCA.

Notably, the quality of fRCA differs from that of Natural Aggregate (NA), characterized by distinct particle size distributions and water absorption properties. While fRCA can effectively replace NA in mortar mixtures, it does affect compressive strength due to higher water absorption and the partial retention of cementitious material. However, by milling or treating it with ACID, the quality of fRCA can be improved, making it possible to use fRCA as a replacement for NS in mortars. The optimal substitution rate of NA with fRCA is identified as 25%, with the possibility of an increase to 100%, depending on the specific application. The integration of fRCA in concrete holds potential for sustainability by reducing reliance on natural resources and curbing waste generated by the construction industry.

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List of Abbreviations

ADR: Advanced Dry Recovery

C2CA: Concrete to Cement and Aggregate

CDW: Construction and Demolition Waste

CS: Compressive Strength

EoL: End-Of-Life

fRCA: Fine Recycled Concrete Aggregate

HAS: Heating air and classification system

NCA: Natural Concrete Aggregate

NS: Natural Sand

PSD: Particle Size Distribution

RAC: Recycled Aggregate Concrete

SG: Specific Gravity

WA: Water Absorption

W/C Ratio: Water/Cement Ratio

1. Introduction

1.1 Background

There is an increasing need for sand within the construction sector. This especially used in concrete mixes because of the need for new houses and facilities. Sand is extracted from riverbanks. Due to the rising demand, more sand is being extracted than what the rivers transport. This changes the river's morphology (Nedeljković, 2021). This raises the question whether there is an alternative for sand to address the increasing demand sustainably.

This bachelor's thesis examines the option of using fRCA (Fine Recycled Concrete Aggregate) in mortar mixes, which is a sustainable option for replacing natural sand (NS). fRCA is already used in various sectors for example, road construction (Fanijo, Kolawole, Babafemi, & Liu, 2023), but that is downcycling. fRCA consists of a sand and cement matrix. By removing the cement residues, it is expected that fRCA can replace a part of the fine sand needed in mortar mixes.

1.1.1 Problem definition

The 'Netherlands Circular 2050' gives the Dutch government's vision on the circular economy. The goal is to achieve a fully circular economy by 2050. To achieve this goal, alternative materials must be introduced. It is widely recognized that recycled construction materials derived from demolition waste (RCA) are an excellent example of a material that can replace Natural Concrete Aggregate (NCA) in construction applications (Suhendro, 2014).
Many obstacles impede the use of fRCA. The obstacles faced in the practical implementation of fRCA in concrete/mortar is summarized as follows:

- **Variations of fRCA properties:** The variations in physical and chemical properties of fRCA cause a wide range of mechanical and durability properties of mortars and concretes with fRCA and make material delivery inconsistent.
- **Costs:** The fRCA contain adhered mortar. It's costly to improve quality of fRCA.
- **Standards:** There is a lack of well-developed guidelines for the quality control of fRCA and wider use of fRCA in new concrete.
- **Research vs practice:** The quality control of recycled fine aggregate (fRCA) in laboratories is considerably stricter and more demanding than in concrete factories. When using fRCA in concrete factories, the main concerns are: the unknown origin of fRCA, scale-up and the lack of testing guidelines. This makes the application of different types of fRCA extremely challenging in practice.

1.1.2 Project description

1.1.2.1 C2CA technology

Recycling of concrete at the end of its life (EoL) is a critical issue as EoL concrete constitutes up to 40 – 50% of construction and demolition waste (CDW), which in turn accounts for up to 33% of total solid waste in Europe. Concrete is the largest source of solid waste in Europe (Gebremariam et al., 2020). Reusing EoL concrete contributes significantly to reducing CO2 emissions associated with activities in the construction sector.

The EoL concrete can be broken down into two valuable components: cement and high-performance aggregate. This is where the Concrete To Cement Aggregate (C2CA) technology comes in, which has developed the world's first mobile factory for circular concrete (Di Maio, 2012).

The primary goal of C2CA technology is to provide a structured and cost-effective approach to the reuse of EoL concrete. This innovative technology is used to produce recycled concrete aggregate (RCA) with minimal contamination and improved mechanical properties of the materials on site. Figure 1.1 shows which processes exist in a C2CA technology. The additional processes from this research have been added in the green rectangle.

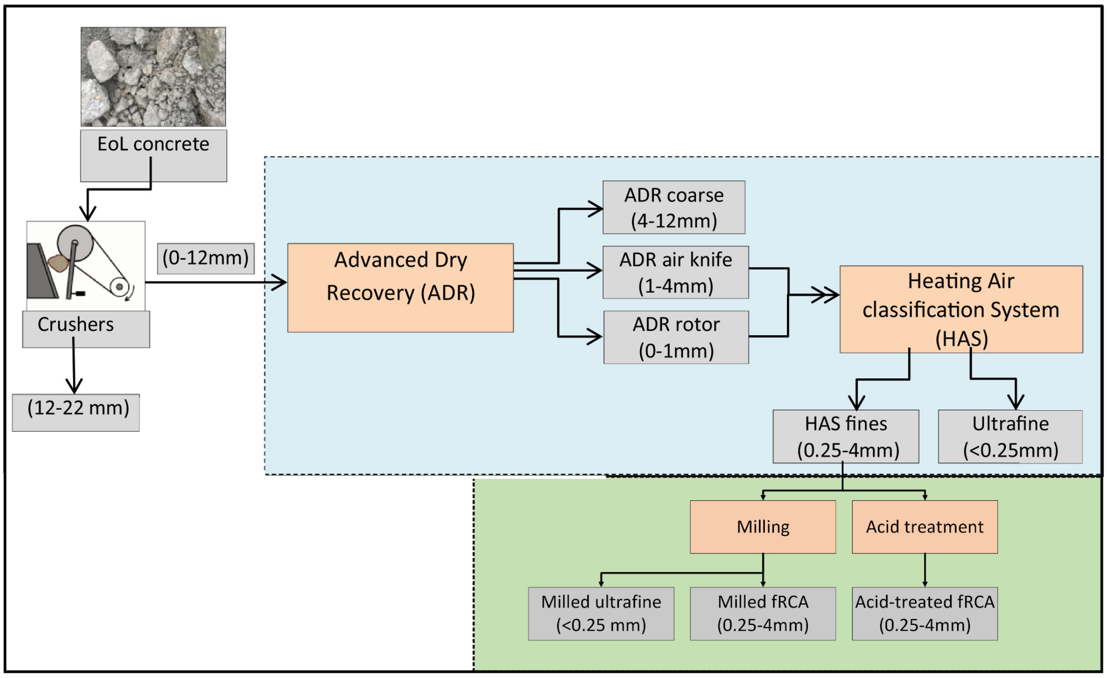


Figure 1.1: A sketch of processing EoL concrete by using ADR and HAS technologies (Gebremariam et al., 2020)

The primary objective of C2CA technology is to facilitate the on-site recycling of concrete rubble. In pursuit of this goal, a cost-effective treatment technique has been recently pioneered in the Resources and Recycling Lab at TU Delft, known as Advanced Dry Recovery (ADR), as detailed by Gebremariam et al. in 2020. A key feature of ADR is its utilization of the kinetic energy principle generated by the rotor, which effectively severs the water bonds between fractions. Consequently, this innovation enables the separation of particles of varying sizes, ultimately resulting in the production of crushed aggregates.

After that, the fine fraction (0-4 mm) produced by ADR is treated by a Heating Air System (HAS) also shown in Figure 1.2. By treating these materials with hot air in a fluidized reactor, the fine aggregates are dried and unwanted contaminants such as wood and plastic are removed. The use of heating is also to somehow activate the ultrafine particles, which mainly consist of hydrated cement. The technology uses air flow to classify the aggregates by size. The distinguishing feature of HAS is the presence of horizontally arranged tubes in the vertical chamber, which expose aggregates to heat for a longer period of time for efficient transfer. This process results in the separation of the fine fraction, while the coarser particles are removed. Fine aggregates produced by HAS are the fRCA utilized in this study.

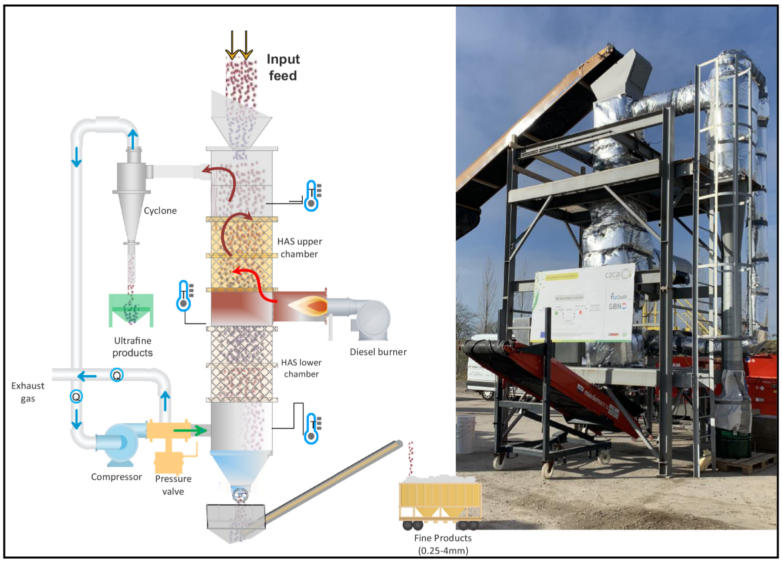


Figure 1.2: A sketch of heating air classification system (HAS) for recycling concrete fines, where the measurement points are indicated as Q for flow and T for temperature (Left). 3 t/h HAS facility at site in Hoorn, Netherlands (Right) (Gebremariam et al., 2020).

1.2 Objective

This research focuses on how fRCA can replace a part of the fine sand needed in mortar mixes. The objectives of this research are as follows:

- Characterizing the properties of fRCA:
    - The aim of this research is to thoroughly characterize the properties of fRCA.
- Enhancing the quality of fRCA through:
    - Trying to improve the quality of fRCA through:
        a. Acid treatment.
        b. Milling of fRCA.
- Investigating the impact of the water-cement ratio (W/C) on mortar workability:
    - Trying to examine the influence of the W/C ratio on the workability of mortar with fRCA.
- Assessing the compressive and tensile strength of mortar with fRCA:
    - The compressive and tensile strength of mortar with fRCA will be determined.

1.3 Research questions

- Research question:
    - What is the best way to improve the properties of fRCA and use it in concrete mixes for civil engineering applications?
- Sub questions:
    - *Which properties of fRCA affect the performance of concrete mixes?*
    - *How to improve the quality of fRCA?*
    - *How does the water to cement ratio and the amount of cement paste on fRCA surface influence the workability of concrete mixes?*
    - *What is the optimum amount of fRCA to use to replace natural sand in a mortar mix?*
    - *How sustainable is the new mortar mix made of fRCA?*

1.4 Scope

The scope of this research includes:

- Types of fRCA: The research focuses on fRCA (HAS produced) containing pure sand mixed with cementitious material, with all other substances such as wood or steel already removed.
- Treatment methods: The study will investigate the effects of all of untreated fRCA, milled fRCA and acid washed fRCA on the properties of the mortar.
- Replacement Ratio: The study will determine the optimum quantity of this milled pure fRCA that can replace natural sand in mortar mixes.
- Sustainability assessment: The sustainability of mortar mixes with this specific pure fRCA will be evaluated theoretically.
- Research Limitations: Practical sustainability assessments are not included in this research scope, all tests are conducted in a laboratory setting and the time limitation of 8 weeks. This research does not dive into the chemical properties.

1.5 Methodology

First, a literature study is conducted into the properties of fRCA and how these properties can be improved. At the same time, laboratory tests are carried out to apply the findings from the literature.

In the laboratory:
First, the materials are prepared. After material preparation, the properties of the materials are determined to determine a suitable mortar mixture. After the mixture is made, the mortar is cast and subjected to tests to measure its strength and workability. These tests are performed at intervals of 2, 14 and 28 days. Further details on this can be found in Chapter 3.1 Methodology and Materials.

Figure 1.3 shows the workflow followed to obtain the research objectives defined in the study.

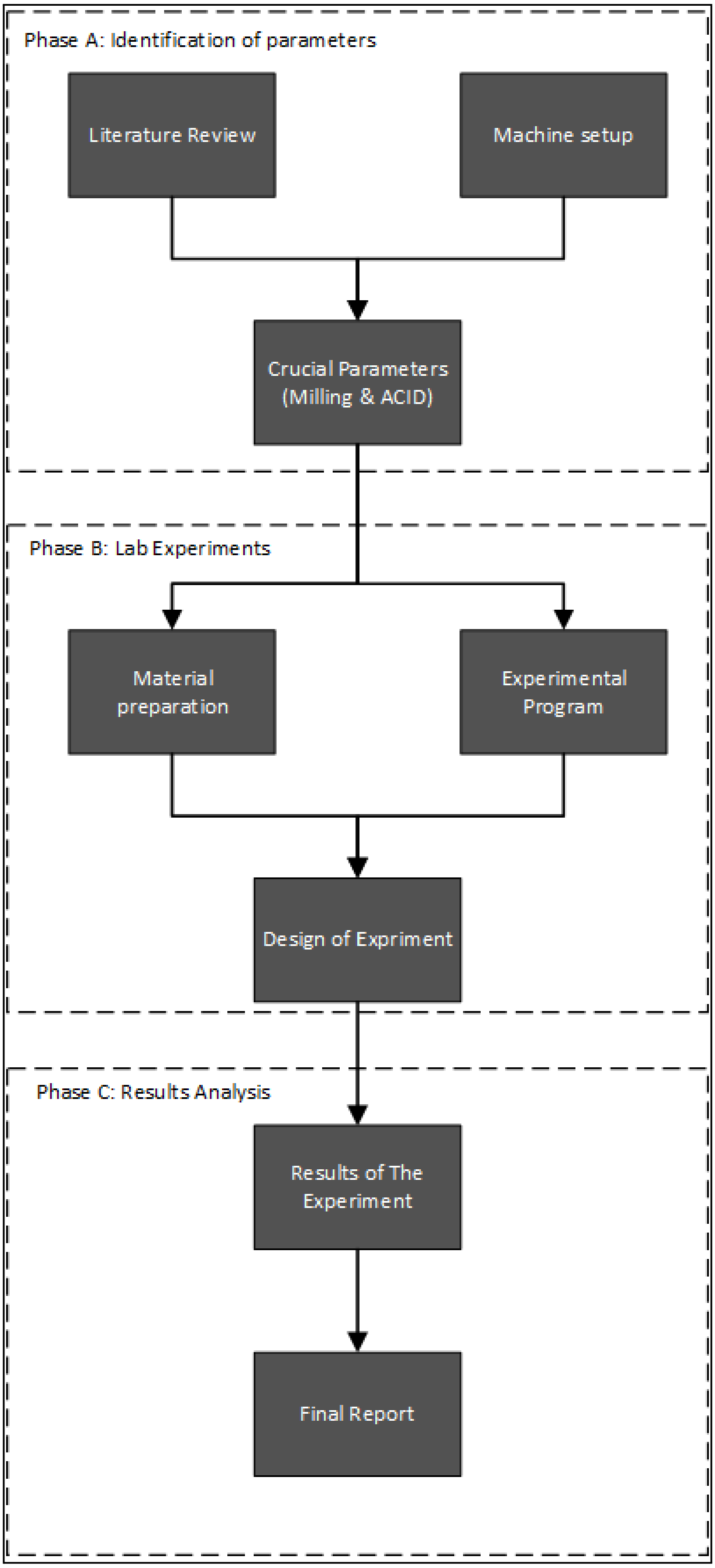


Figure 1.3: Workflow followed to obtain the research objectives defined in the research.

2. Literature Review

This chapter examines the properties of fRCA as mentioned in the literature. Furthermore, it assesses the quality of fRCA. Afterward, it describes the using of fRCA in mortar mix. Finally, it delves into the sustainability aspect of incorporating fRCA into concrete.

2.1 Properties of fRCA

The physical and chemical properties of fRCA can vary widely, which can affect the mechanical and durability properties of mortar and concrete made with it. This can also make it difficult to ensure consistent material delivery (Nedeljković, 2021). It can vary depending on the parent concrete and the recycling process. However, in general, fRCA with a well-graded particle size distribution, angular particle shape, and low water absorption will produce concrete with better workability and strength. (Sosa, 2023)

2.1.1 Physical properties

This section highlights important physical properties of fRCA, such as Particle Size Distribution, Water Absorption, Moisture states, and Density. These properties are essential to understanding and managing the performance and sustainability of the mortar/concrete mix. (Rodrigues, 2013)

2.1.1.1 Particle size distribution

Particle size distribution (PSD) is a critical characteristic of aggregates as it profoundly impacts the workability, strength, and durability of concrete. fRCA generally exhibit a finer PSD compared to traditional concrete aggregates (Nedeljković, 2021). This can result in several issues:

- **Reduced Workability:** Fine particles can elevate the water demand of the concrete/mortar mixture, leading to decreased workability. This makes it more challenging to properly place and shape the concrete or work with mortar.
- **Reduced Strength:** The existence of fine particles can reduce the strength of the concrete by increasing its porosity. This increased porosity can weaken the overall structural integrity of the concrete.

2.1.1.2 Water absorption

Water absorption is the amount of water that an aggregate can absorb. It is a significant property of aggregates because it affects the workability, strength, and durability of concrete and mortar. fRCA typically exhibits higher water absorption compared to conventional concrete aggregates/natural sand due to its elevated porosity (Nedeljković, 2021). This can result in several issues:

- **Reduced workability:** fRCA concrete or mortar often requires a higher water content to achieve the same workability as traditional concrete or mortar.
- **Reduced Strength:** The increased water absorption of fRCA can also reduce the mortar's strength by enhancing the porosity of the mortar matrix.

2.1.1.3 Moisture states

In concrete mix design, in addition to WA, the moisture content of the aggregates also plays a significant role. The moisture content of the aggregates has a substantial impact on the rate at which aggregates absorb water. fRCA often exhibits varying moisture content, which increases the required water quantity for cement hydration. fRCA typically shows three moisture states: (i) surface saturated, surface dry, (ii) wet, and (iii) a combination of (i) and (ii) moisture states due to the presence of binder. Consequently, fRCA generally has a higher moisture content than natural aggregates (Nedeljković, 2021).

2.1.1.4 Density

As mentioned previously, fRCA results in increased porosity, which in turn leads to a lower density compared to traditional concrete aggregates. fRCA typically has an average density of 2295 kg/m³, whereas natural fine aggregates have an average density of 2637 kg/m³ (Nedeljković, 2021). This has the advantage of potentially resulting in reduced weight of concrete structures. However, the lower density of fRCA can also bring about some cons, such as reduced strength.

2.1.2 Chemical composition

fRCA is made from recycled concrete, which consists of cement, sand and water. The chemical composition of fRCA is therefore comparable to that of traditional concrete.
In general, fRCA consists of impure aggregates. Within fRCA there are found materials such as wood, iron/steel, various plastics and polymers, glass and vegetable fibers (Nedeljković, 2021). A study about the chemical composition of construction and demolition (C&D) waste recycled aggregates shows that the main oxides were SiO2 (48,0–84,2%), Al2O3 (5,0–17,2%) and CaO (2,4–13,9%), followed by high LOI values (3,4–19,6%) (Angulo, 2009).

fRCA also contains contaminants that are concentrated in the finest fraction of the fRCA. This concerns Cl− and SO42− and soluble alkalis. The chloride content in concrete must be limited to prevent corrosion of steel reinforcement. Excess internal sulfate content can cause internal sulfate attack. The Na2O equivalent of cement used for specific concrete are limited in standards to a certain value in order to prevent deleterious alkali aggregate-reaction and amplification of internal sulfate attack (Nedeljković, 2021).

2.1.3 Quality of Fine Recycled Concrete aggregates (fRCA)

The main difference between NCA and fRCA is that in fRCA are cement and contaminants present. The presence of cement and contaminants mainly affect the physical properties which directly impact the mechanical properties of Recycled Aggregate Concrete (RAC). Also, fRCA have different particle size distributions, water absorption and tend to be angular with rougher surfaces compared to NCA. These differences will significantly impact the packing density, the workability, and strength of the new concrete mixtures.

2.2 Using of fRCA in mortar mix

Mortar consists of three basic ingredients: cement, sand (fine aggregates) and water.
As mentioned in section 2.1.3, the main difference between fRCA and NCA is the hardened cement paste in the composition of fRCA. By removing the contamination in fRCA, fRCA could replace the NCA. The properties of fRCA must also be compared with those of NCA in order to use fRCA instead of sand, so that the compressive strength of the mix is not greatly impacted.

A study by Sosa M. E.(2021) concludes that compressive strength seems to be particularly impacted by how fRCA water absorption is taken into account in mix proportioning. The study also noted that there is a decreasing trend in compressive strength with the increase of fRCA content, especially when the fRCA replacement ratio is above 50%. A general trend shows that the compressive strength is weakest at 100% fRCA. It is important to add that in this study the fRCA were used in saturated surface dry condition (ssd). The amount of water used to reach the ssd condition in the fCRA is determined with a water absorption measurement. The same study also shows that the method by which water absorption is determined is of great importance, as the results of the different methods differ. If the amount of water is higher than required to reach the ssd condition, free water could be unintentionally introduced into the mix. The higher the content of fRCA, the higher the free water content, and the greater the differences in compressive strength. This free water content in mortars will affect the water/cement (w/c) ratio.

Therefore, adding fRCA in SSD condition is important to avoid changes in the effective w/c, because dry fRCA does not reach full saturation during mixing. A range for the saturation degree from 49 to 89% has been reported in the study of Sosa M. E. (2021).

Another study by Martínez-García et al. (2021) concludes that the optimal percentage of substitution of NCA for fRCA is 25% with respect to compressive and flexural strength tests.

It is observed that an increase in replacement of NCA with fRCA results in an increase in the W/C ratio to achieve adequate workability levels to obtain a consistency similar to that of the reference mortar.

The higher the fRCA content, the higher the loss in compressive strength is observed. This loss in strength decreases when increasing the curing period.

The results of flexural strength at 90 days do not show a significant difference for reference and recycled mortar. That indicates that the replacement of NCA with fRCA does not significantly affect its properties.

2.3 The sustainability aspect of implementing fRCA in concrete

Ensuring the availability of new materials such as recycled materials without resource depletion supports the sustainability of society (Pacheco-Torgal (2014)).
The sustainability of mortar mix made of fRCA is high, as it can help to reduce the use of natural resources and the amount of waste generated by the construction industry. Arabani and Azarhoosh (2012) reported that nearly 75% and 70% of global construction and demolition (C&D) sites, respectively, are wastes from concrete, with the concrete industry being the most unsustainable sector not only due to the steel and cement production, but also the wastes disposal into landfills. Figure 2.1 shows A typical composition of construction and demolition wastes.

As mentioned in the introduction, there is increasing in the need for sand within the construction sector. This especially used in concrete mixes because of the need for new houses and facilities. Due to the rising demand, more sand is being extracted than what the rivers transport. This changes the river's morphology, mentioned in the study of Nedeljković, (2021).
Fanijo et al. (2023) mentioned that the concrete industry generates approximately 50% of total construction waste from a large number of natural resources. In that waste generated from concrete is a major part of construction and demolition waste.

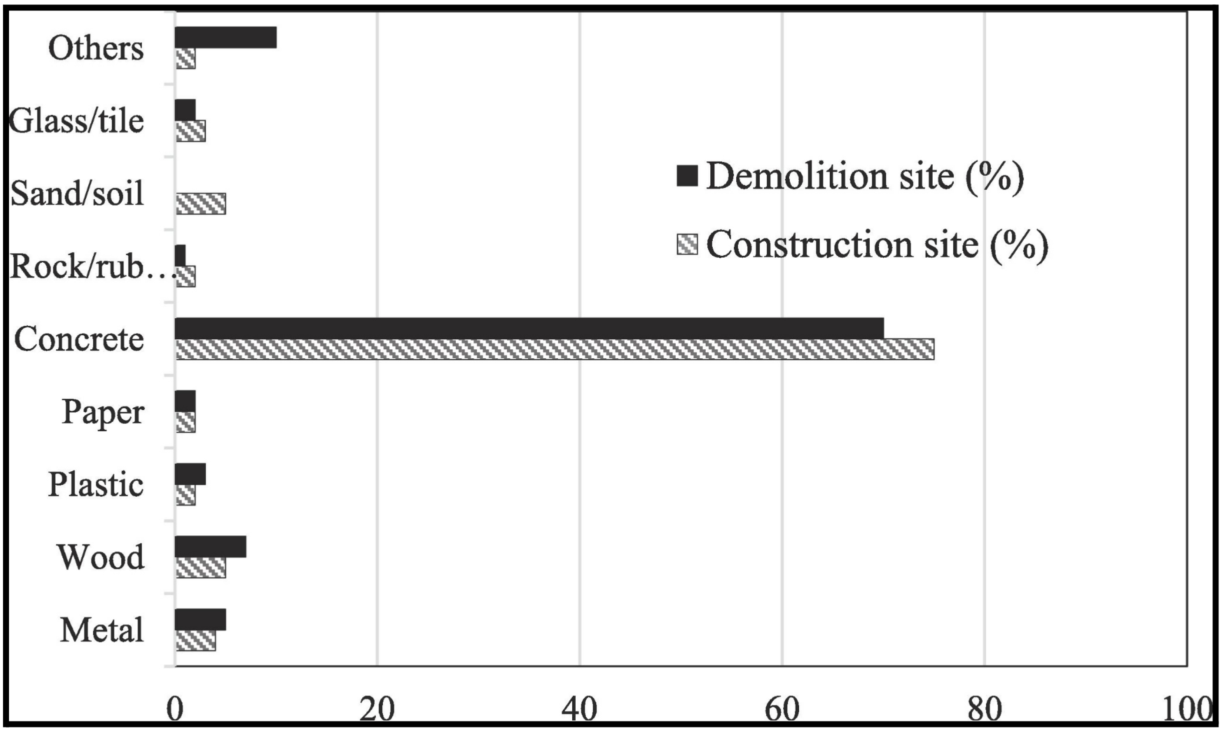


Figure 2.1: A typical composition of construction and demolition wastes (Arabani and Azarhoosh, 2012).

Martínez-García et al. (2021) mentioned that 35% to 45% of NCA used in concrete manufacture is fine NCA. Sosa et al. (2021) mentioned that the replacing of fine NCA with fRCA can have a positive impact on the sustainability of concrete production. However, there are some challenges associated with the use of fRCA, such as the varying properties of fRCA, contamination, and mix design adjustments

2.3.1 Factors influencing the adoption of fRCA

2.3.1.1 Drives of implementing fRCA in concrete

- **CO2 reduction:** Sand and gravel are the most extracted materials, surpassing fossil fuels (Bendixen et al., 2019). Using recycled materials save a significant amount of energy and reduces the amount of CO2, NOx, and other air pollutants emitted from the manufacturer of aggregates. The production of 1 ton of natural aggregates (river sand and crushed stone) results in the emission of 23–33 kg of CO2-equivalents, whereas the production of 1 ton of fRCA from C&DW generates 12 kg of CO2-equivalents (Hossain et al., 2016). That is more than 2 times less CO2 emissions fRCA production than natural aggregates production.

- **Scarcity of raw materials:** Sand and gravel are being extracted faster than they can be replaced (Bendixen et al., 2019). About 32 to 50 billion tons are utilized worldwide each year, mainly for the production of concrete, glass, and electronics. According to Peduzzi's study in 2014, an even higher volume was reported, about 47 and 59 billion tonnes of material is mined every year. This consumption surpasses the rate of natural replenishment to the extent that by the middle of the century demand may exceed supply. A lack of knowledge and monitoring contribute to this unsustainable exploitation (Bendixen et al., 2019).

- **Costs:** fRCA is cheaper than river sand. As long as this is cheaper than natural aggregate, it will be desirable to use RCA in concrete production. Furthermore, reducing natural aggregate extraction can reduce utility and biodiversity costs (Tam et al., 2018). Figure 2.2 shows the sand availability, demand, and price developing between 1900 and 2100.

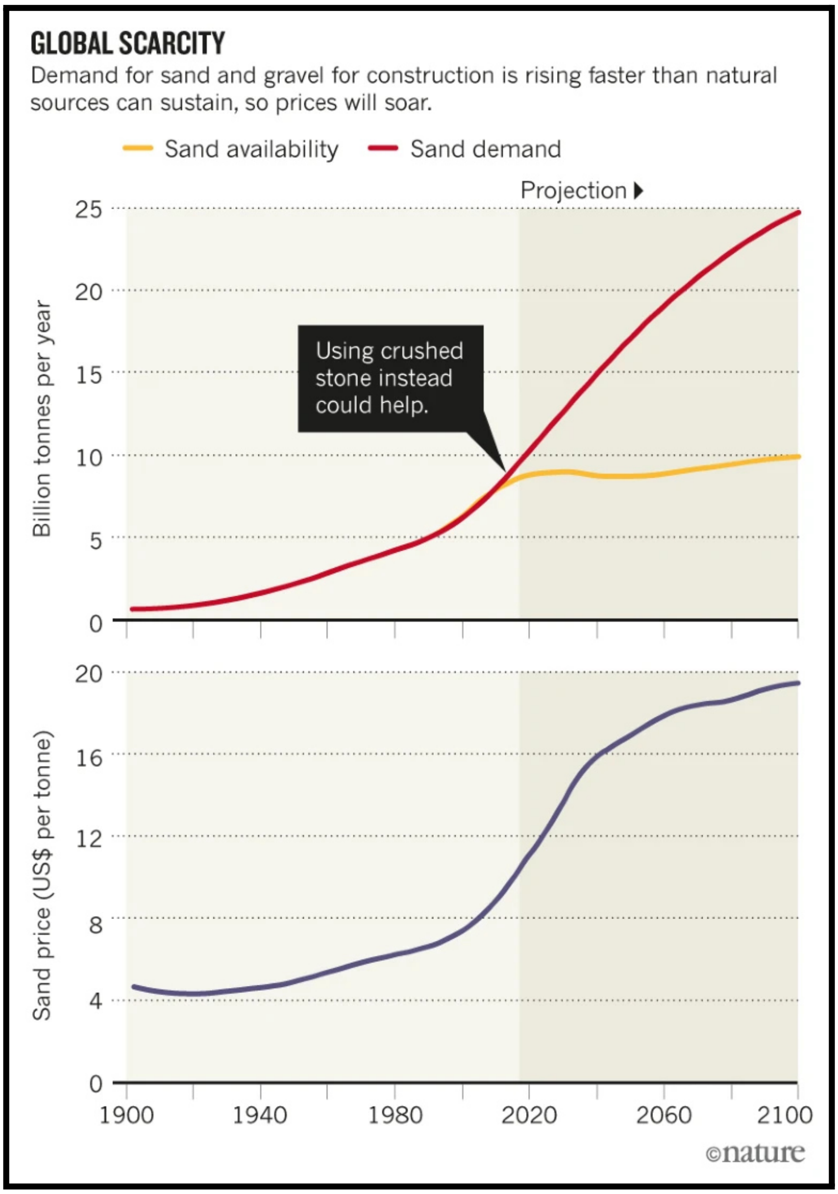


Figure 2.2: Sand availability, demand, and price developing (1900-2100) (Bendixen et al., 2019)

- **Policy changes:** The Dutch ‘Beton Akkoord’ aims to achieve 100% high-quality reuse of concrete waste by 2030.

2.3.1.2 The challenges associated with the use of fRCA in structural concrete

- **Variations of fRCA properties:** The variations in physical and chemical properties of fRCA cause a wide range of mechanical and durability properties of mortars and concretes with fRCA and make material delivery inconsistent (Nedeljković, 2021).

- **Costs:** In order to improve quality of fRCA, it would be costlier to remove pollution from fRCA particles and clean the material from various impurities (Nedeljković, 2021).

- **Standards:** The lack of a well-developed guidelines for the quality control of fRCA is preventing a wider use of fRCA in new concrete (Nedeljković, 2021).

- **Research vs practice** The quality control of recycled fine aggregate (fRCA) in laboratories is considerably stricter and more demanding than in concrete factories. When using fRCA in concrete factories, the main concerns are: the unknown origin of fRCA, scale-up and the lack of testing guidelines. This makes the application of different types of fRCA extremely challenging in practice (Nedeljković, 2021).

3. Experimental program

3.1. Methodology and Materials

This chapter will start by outlining the required materials for the experiment. Then discussing the methodology.

3.1.1 Materials

In this research, the following materials are used:
Water: Water from the lab was utilized for casting.
Cement: Cement type CEM III/B 42.5 N LH/SR is used.
Recycled Fine Concrete Aggregate: The fRCA is produced with the C2CA technology (HAS), fractions range: 0,25-4 mm.
Natural Fine Aggregate: The NFA aggregate, which is river sand, is taken from the aggregate silo in the TU Delft casting lab, fractions range: from 0,25–4 mm.

All materials are sieved with a sieve diameter 0.25 mm.

- Acid-treated fRCA:
  First, the materials are weighed. They are then soaked for 24 hours in a 5 mol/L HCL solution. They are then washed with water and then dried in an oven at 105 °C for 24 hours. After drying, they are weighed again.
- Milling fRCA:
  First, the optimal method of milling for fRCA is examined. This is done by varying the time and the ratio of mass fRCA/mass of metal balls.

3.1.2 Methodology

3.1.2.1 Used tests

- First physical properties of fRCA
  - Water Absorption
  - Specific Density

- Determination of strength:
  This method involves the determination of the compressive strength of prism test specimens with dimensions of 40 mm × 40 mm × 160 mm.
  The NEN-EN 196-1 will be used for this test.
  Each batch of three test specimens shall consist:
  - (450 ± 2) g of cement
  - (1 350 ± 5) g of sand
  - (225 ± 1) g of water.
  - W/C ratio = 0,5

- Determination of the consistency of fresh mortar (with shock table):
  The flow value is measured by the mean diameter of a test sample of the fresh mortar which has been placed on a defined flow table disc by means of a defined

mould. The test sample is given a number of vertical impacts by raising the flow table and allowing it to fall freely through a given height.
The EN 1015-3:1999 will be used for this test.

- The fresh mortar for this test shall have a minimum volume of 1,5 l and shall be obtained by reduction of the bulk test sample (see EN 1015-2) using a sample divider or by quartering.

- Determination of flexural and compressive strength of hardened mortar:
  The flexural strength of mortar is determined by three point loading of hardened moulded mortar prism specimens to failure. The compressive strength of the mortar is determined on the two parts resulting from the flexural strength test. Where the flexural strength is not required, the parts for compressive strength testing can be produced from the prisms in any way which does not lead to these parts being damaged.
  The NEN-EN 1015-11 will be used for this test.
  - The test specimens shall be prisms 160 mm x 40 mm x 40 mm. Three specimens shall be provided.

3.1.2.2 Mix designs

The tests are conducted on 7 different mortar mixes, these are presented in Table 3.1.

Table 3.1: The required materials for 1 test according to the NEN-EN 196-1 (in grams) with W/C ratio = 0,5.

Sample	Water	Cement	Sand	untreated fRCA	Acid-treated fRCA	Milled fRCA
Ref 100% natural sand	225	450	1350	0	0	0
100% untreated fRCA	225	450	0	1350	0	0
100% Acid-treated fRCA	225	450	0	0	1350	0
100% milled fRCA	225	450	0	0	0	1350
75% milled fRCA, 25% natural sand,	225	450	337,5	0	0	1012,5
50% milled fRCA, 50% natural sand	225	450	675	0	0	675
25% milled fRCA, 75% natural sand	225	450	1012,5	0	0	337,5

4. Results and discussion

In this chapter, the results of the laboratory experiments are presented, starting with the various treatments aimed at improving the quality of fRCA (ACID and milling). Following that, the mix design and the properties of the materials were determined. Finally, the results of mortar testing are presented.

4.1 Treatment of fRCA

fRCA refers to the HAS fines presented in section 1.1.2.1 in Figure 1.1. As mentioned in Section 2.2, It is anticipated that by eliminating the contamination, specifically the cement paste, fRCA has the potential to replace NCA. For the treatment of fRCA, two methods were selected:

1. ACID treatment
2. Milling

4.1.1 ACID-treatment of fRCA

The process begins with the weighing of the materials. They are then subjected to a 24-hour treatment in a 5 mol/L HCL solution. Following the treatment, they are rinsed thoroughly with water and subsequently dried in an oven at 105 °C for 24 hours. Once the drying is complete, their weight is measured again to assess any treatment-induced changes.

To obtain reliable results, a total of 5 different samples were prepared, and each of the 5 samples was treated individually. The results are shown in Table 4.1.

Table 4.1:The ACID-treatment of fRCA results.

Sample	Mass before treatment (gram)	Mass after treatment (gram)	Mass loss (gram)	Percent removal (%)
ACID-1	1004,1	793,4	218,6	21,77
ACID-2	1032,1	815,2	218,9	21,21
ACID-3	1025,5	813,2	242,1	23,61
ACID-4	1012	795,4	262,1	25,90
ACID-5	547,89	436,7	111,19	20,29

To calculate the percent removal, the following equation is used:

$$Percent\ \ removal\,[\%]\ = \frac{Mass\ loss}{Mass\ before\ treatment}\ *\ 100\% \qquad (Eq\,4.1.1)$$

After washing the samples with water, a greenish material was observed, which was later dried, and its mass was added to the mass loss. The mass of this material can be found in Table 4.2. Figure 4.1 shows the dry greenish material. In Figure 4.3 the Acid-treated fRCA are presented and in Figure 4.4A and 4.4B is the PSD of Acid-treated fRCA presented.

Table 4.2: Mass of greenish material in grams.

Sample	Mass greenish material
ACID-1	7.9
ACID-2	2.0
ACID-3	29.8
ACID-4	45.5
ACID-5	0

Figure 4.1: The greenish material after drying.

There is a clear change in the material due to the acid treatment, with an average mass loss of 22,7% observed. Cement is a base material, and adding acid can lead to an acid-base reaction, which may clean the sand in the fRCA, but the exact nature of these changes was not explored in this study. In Figures 4.3 is a picture of Acid-treated fRCA presented, 4.4A,B is the PSD presented and in 4.5A is a microscopic image of the material presented.

4.1.2 Milling of fRCA

Before milling fRCA, it was necessary to optimize the milling parameters. These parameters include the milling duration and the aggregates/balls mass ratio. The parameters for the study were selected based on a trial and error method and the research method of Reddy and Yaragal (2023). The generated combinations can be found in Table 4.3. The used balls had a 4 different diameter, Figure 4.2 shows the balls.

The results of the milling process using the parameters selected from Table 4.3 are displayed in Table 4.4.
To calculate the percent removal, the following equation is used:

$$Percent\ removal\ [\%] \ = \frac{Mass\ loss}{Mass\ fRCA\ after\ milling} \ * \ 100\% \qquad (Eq\ 4.1.2)$$

Figure 4.2: Steel balls used for milling

Table 4.3: Optimisation of Milling process parameters.

Sample	Duration (min)	Mass ratio fRCA/balls
1:6 10 min	10	1/6
1:5 10 min	10	1/5
1:4 10 min	10	1/4
1:3 10 min	10	1/3
1:6 20 min	20	1/6
1:5 20 min	20	1/5
1:4 20 min	20	1/4

Table 4.4: Milling optimisation experiment results

Sample	Steel balls mass (gram)	Duration (min)	Mass of aggregates (gram)	Mass ratio fRCA/balls	Mass aggregates after milling (gram)	Mass loss (gram)	Precent removal (%)
1:6 10 min	1203,8	10	199,7	1/6	150,5	47,7	31,7
1:5 10 min	1011,2	10	202,8	1/5	158,4	43,6	27,5
1:4 10 min	802,6	10	202,2	1/4	165,8	35,8	21,6
1:3 10 min	3028,7	10	1021,1	1/3	992,6	11,6	1,2
1:6 20 min	3003,5	20	499,7	1/6	350,2	148	42,3
1:5 20 min	2503,5	20	500,9	1/5	387,2	111,5	28,8
1:4 20 min	2004,1	20	502,9	1/4	373,9	65,5	17,5

The PSD of the samples was the determining factor in identifying which milling parameter combinations best matched the PSD of the ACID-treated fRCA. All samples are presented in Figure 4.3. All the PSDs are presented in Figure 4.4A. It was observed that the sample with a mass ratio fRCA/balls of 1:6 and a milling time of 20 minutes had the highest percent removal. However, it was noted that the material had been milled to such an extent that it turned into a powder. This was the case with all the other samples as well, except for those with a mass ratio fRCA/balls of 1:3 and 10 minutes of milling. This observation is also visible in Figure 4.4A, where the untreated fRCA is also plotted, also to illustrate this comparison clearly, Figure 4.4B was created. All the PSDs have shifted to the left, indicating that the materials have become finer. The fining of materials implies that bonds have been broken in the fRCA, and particles have been released. However, this research did not investigate the nature of these fine particles.

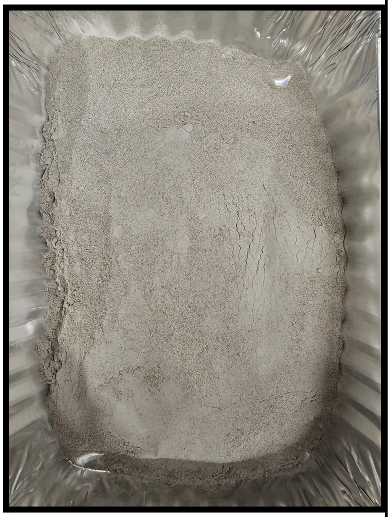
After combining the PSD of Acid fRCA with the milled ones, it was determined that the sample with mass ratio fRCA/balls 1:3 and 10 minutes of milling provided the closest match to the PSD of the Acid-treated fRCA.

From now on, the sample with mass ratio fRCA/balls of 1:3 and 10 minutes of milling will be referred to as "Milled fRCA."

a) 1:6 ratio 10 min Milled fRCA

b) 1:5 ratio 10 min Milled fRCA

c) 1:4 ratio 10 min Milled fRCA



d) 1:6 ratio 20 min Milled fRCA

e) 1:5 ratio 20 min Milled fRCA

f) 1:4 ratio 20 min Milled fRCA

g) Natural Sand

h) Acid-treated fRCA

b) 1:3 ratio 10 min Milled fRCA

Figure 4.3: Materials pictures

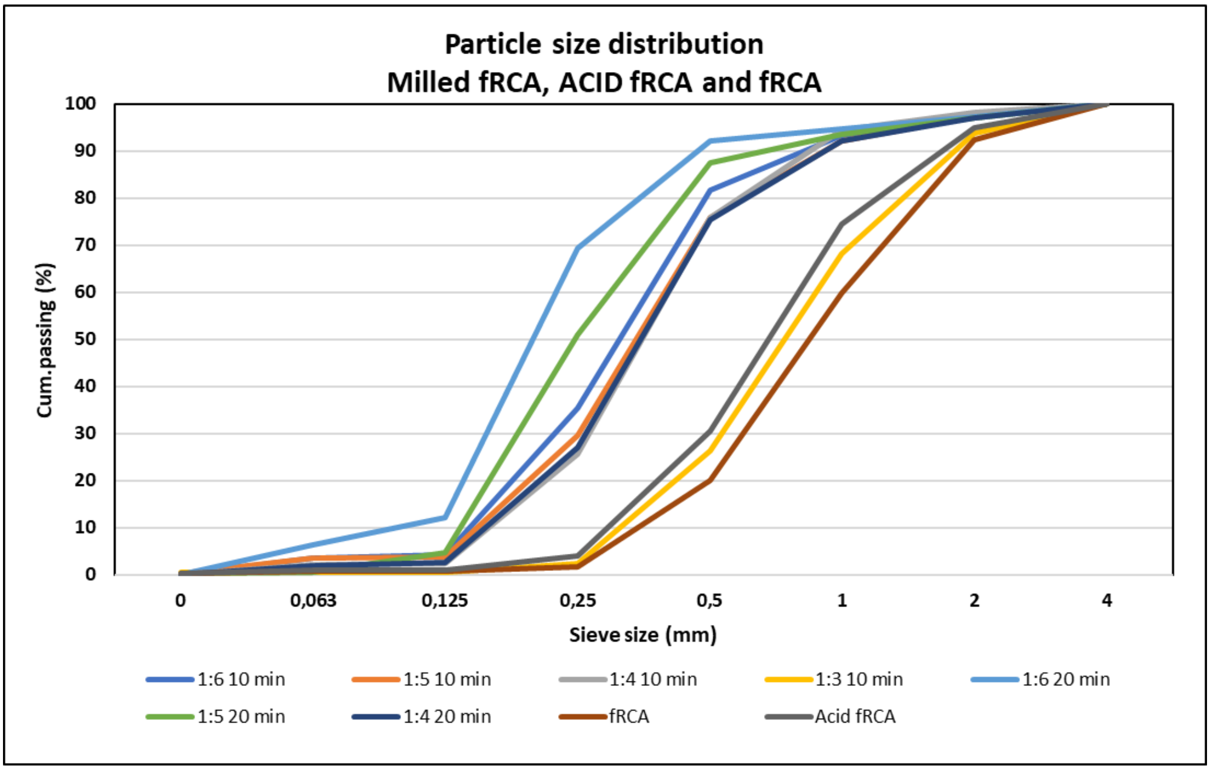


Figure 4.4A: The particle size distribution of the milled samples, ACID-treated fRCA and fRCA

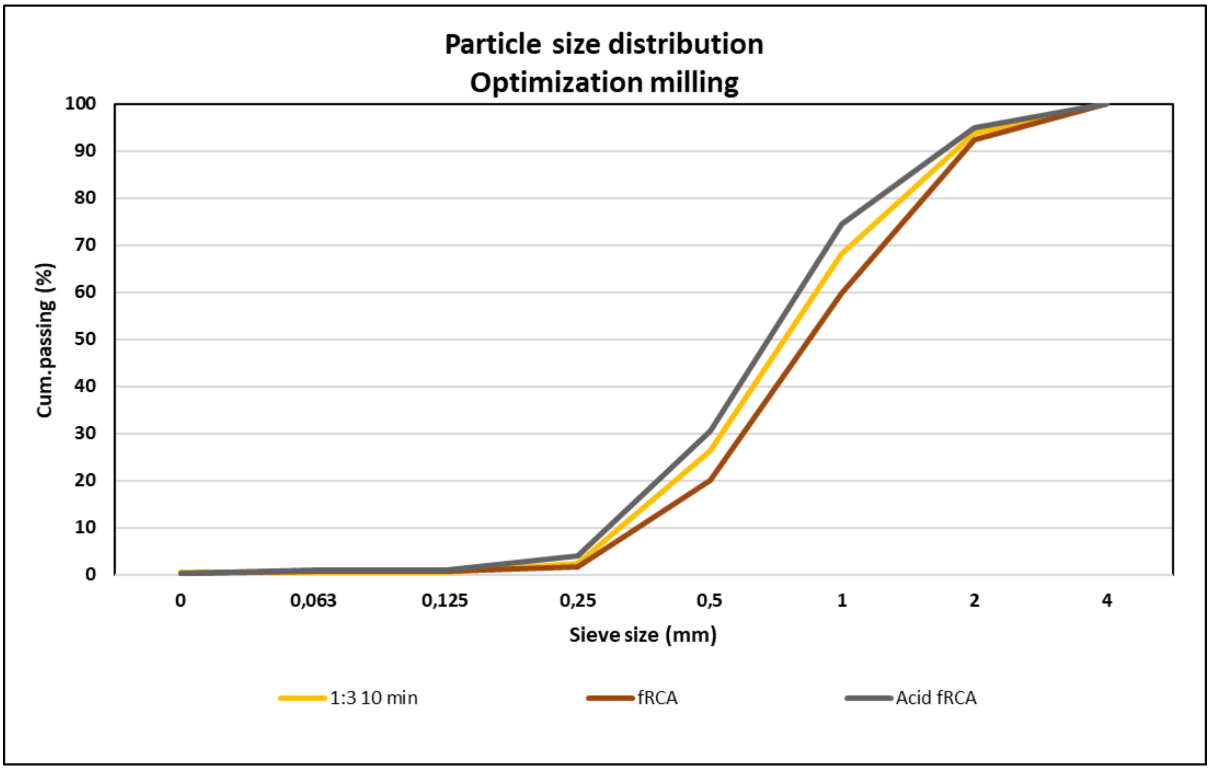


Figure 4.4B: The particle size distribution of the sample with a 1:3 ratio and 10 minutes of milling, ACID-treated fRCA, and fRCA

4.1.3 fRCA-Treatments discussion

As shown in Figure 4.5A, the acid-treated fRCA appears to have become completely clean after the treatment. On the other hand, it is more challenging to observe in the milled ones. To assess this, it was necessary to examine the particles of milled fRCA and compare them to fRCA particles. This can be seen in Figure 4.5B, where it's apparent that milled fRCA has notable cracks on the cement surfaces. This leads to the conclusion that the milled ones have also become cleaner, though not entirely clean.

a) Natural sand

b) fRCA

c) Acid-treated fRCA

d) Milled fRCA

Figure 4.5A: A microscopic image of the materials.

a) fRCA

b) Milled fRCA

Figure 4.5B: A microscopic image of a) fRCA particle and b) milled fRCA particle.

4.2 Mortar mix design

Following the milling optimization and ACID treatment of fRCA, the next step involved the mortar mix design in preparation for material processing. The PSD of the materials created after optimizing the milling process is displayed in Figure 4.6. In this figure, the weight percentage is depicted as a bar chart, facilitating the easy comparison of the PSDs.

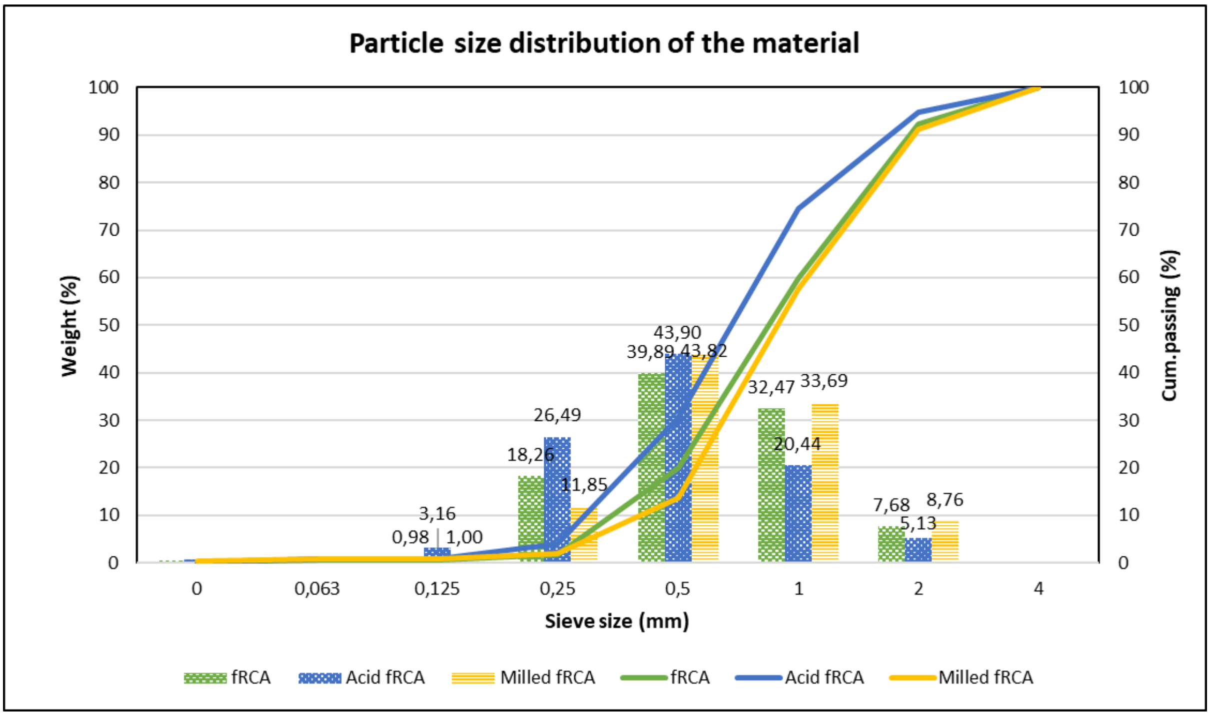


Figure 4.6: The particle size distribution of the materials used in the mortar mix.

It is noteworthy that the milled fRCA displays a coarser fraction in the PSDs in Figure 4.6. This was not the expected outcome after optimizing the milling process. All the materials used were taken from the same fRCA source. One possible explanation for this pattern is the variability in the supply of fRCA, as mentioned in the literature. However, this does not impact the results of this research because a uniform PSD is defined that all materials must meet. The effect of the coarser fRCA is that more material needs to be milled to achieve the uniform PSD.

To define the uniform PSD, the mix used by the NEN was evaluated, and it is presented in Table 4.5A. However, because the used fRCA lacked a fine fraction (as shown in Figure 4.6), an alternative PSD was chosen, shown in Table 4.5B. In this selection, only the fine fraction was removed. Figure 4.7 displays the PSD of this choice in comparison to the NEN limits.

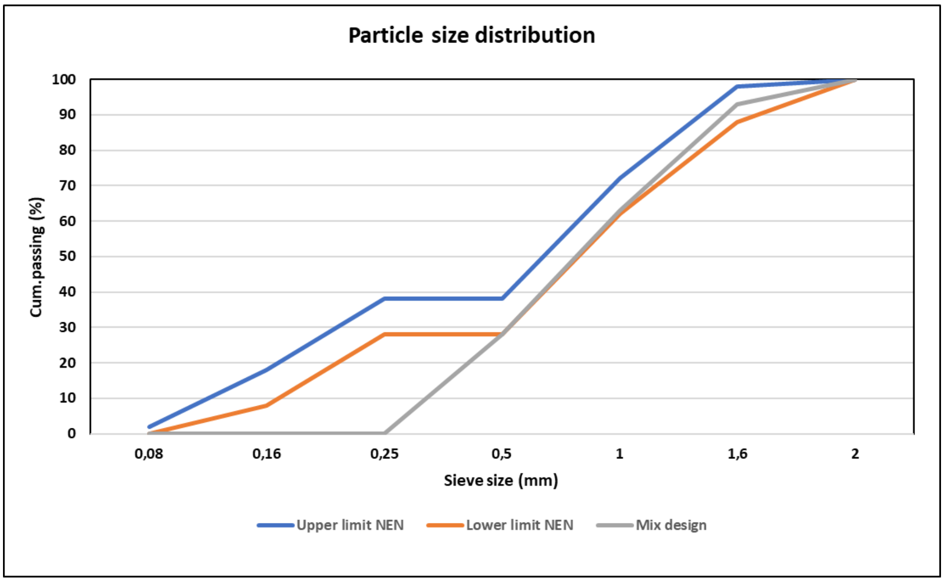


Figure 4.7: The particle size distribution of the sample of the mix design compared to the NEN limits

Table 4.5A: Particle size distribution of the CEN Reference sand (NEN-EN 196-1)

Square mesh size (mm)	2	1,6	1	0,5	0,16	0,08
Cumulative sieve residue (%)	0	7 ± 5	33 ± 5	67 ± 5	87 ± 5	99 ± 1

Table 4.5B: Particle size distribution of the mortar mix used

Square mesh size (mm)	2	1,6	1	0,5	0,25
Cumulative sieve residue (%)	0	7	37	72	100

The same PSD was applied to all samples from Table 3.1. By limiting the variation, the results become less sensitive to this parameter. The requirements for a mortar mix with sand, water, and cement are presented in Table 4.6. These quantities are sufficient for one day of testing. The NEN standard specifies 150% of the amount to ensure an adequate supply of material. However, in this research, it is assumed that 110% will be sufficient.

Table 4.6: The requirements for a mortar mix for 1 day testing

Material	**Water**	**Cement**	**Sand**
Mass (gram)	225	450	1350

4.3 Physical properties

Three physical properties were determined: particle size distribution, water absorption, and specific density. Due to a lack of Acid fRCA material, the water absorption and specific density of Acid fRCA were not determined.

4.3.1 Particle size distribution

The PSD of the materials used in the mortar mix is presented in Figure 4.7.

4.3.2 Water absorption and specific density

Water absorption and specific gravity were determined in accordance with NEN-EN 1097-6 for the sand, fRCA, milled fRCA, and ACID fRCA as presented in Table 4.7. The used worksheets, photos of the research in the lab, and the results can be found in Appendix A.

Table 4.7: The Water Absorption, Specific Gravity, and Apparent Specific Gravity of the materials

Parameter	Sand	fRCA	Milled fRCA	ACID fRCA
Specific Gravity	2,55	2,09	2,14	-
Apparent Specific Gravity	2,61	2,44	2,51	2,61
Water Absorption (%)	0,84	6,96	6,85	-

The determination of WA involved a subjective assessment of the SSD condition. The test was performed twice because the SSD condition was not adequately judged the first time. As a result, the first attempt at calculating WA did not align with the literature. However, the second attempt provided a better definition of SSD, and the resulting WA values were more comparable to those found in the literature. The WA of ACID-treated fRCA was initially determined, but due to an inaccurate SSD condition, the result was not accurate. Unfortunately, because the material supply was insufficient, it was not possible to re-determine the WA.

The water absorption of fRCA indeed seems to be significantly higher than that of sand and this observation aligns with the explanation provided in the literature, attributing it to the higher porosity of fRCA compared to sand. It is noted that porosity was not investigated in this study, as it was outside the scope of the research. It's also observed that after treating fRCA through milling, WA did not significantly improve. To make a valid assessment in this regard, it is essential to determine the porosity of the fRCA before and after milling. By combining these two sets of data, conclusions can be drawn about why the WA does not significantly change. However, based on the change in specific gravity, an assumption can be made. When specific gravity increases, porosity decreases. Specific gravity is a measure of the density of a material relative to water. The specific gravity after milling appears to have improved. A higher specific gravity indicates that the material is denser than water. Higher density implies that there is less space for pores. Therefore, it is expected that the WA of fRCA should be significantly improved after milling. The fact that this improvement is not evident in the WA determination may still be attributed to the difficulty in accurately defining the SSD condition of the materials.

4.4 Mortar Testing

In this section, the mortar mix used is presented, followed by the consistency test results and the outcomes of the flexural strength and compressive strength tests in 2, 14, and 28 days. In Appendix B and C, respectively, the worksheets for the tests, along with the individual test results, can be found.

4.4.1 Mortar mix and casting

By utilizing Table 4.5B, the quantities of materials are prepared per sieve size, and then the precise amount for each size is added to each mix. In Table 4.8A and B, the exact quantities are specified. More information on why additional water was required for some mixes to achieve the necessary workability is reported in section 4.4.2. A total of 58 specimens were prepared. In Figure 4.8A and 4.8B, the specimens are visible during casting and after 2 days in the storage curing room.

Table 4.8A: The quantities of used materials (in gram)

Sieve size (mm)	0,25	0,5	1	1,6	2	Total Mass
Sand	3118,5	3898,1	3341,3	779,6	0	**11137,5**
fRCA	1247,4	1559,3	1336,5	311,9	0	**4455**
Milled fRCA	3118,5	3898,1	3341,3	779,6	0	**11137,5**
Acid fRCA	457,4	571,7	490,1	114,3	0	**1633,5**
Cement	-	-	-	-	-	**9415,9**
Water	-	-	-	-	-	**5507,7**

Table 4.8B : The specimens made

Material	*Ref 100% natural sand*	*100% untreated fRCA*	*100% Acid-treated fRCA*	*100% milled fRCA*	*75% milled fRCA*	*50% milled fRCA*	*25% milled fRCA*
Specimens	*9*	*9*	*4*	*9*	*9*	*9*	*9*

Figure 4.8A: Casting the mortar

Figure 4.8B: After 2 days mortar storage in curing room

After casting 3 mortar prisms with 100% Acid-treated fRCA, it was discovered that an additional prism could be cast. This additional prism was indeed created and is intended for a measurement after 14 days. Additional water was also added to certain mixes, as can be seen in Table 4.9, and this will be discussed in more detail in the following section.

4.4.2 The consistency of the fresh mortar

The results of the consistency test for fresh mortar are presented in Table 4.9. The test is considered successful if the individual flow values from the two test samples deviate from their mean value by less than 10%. In such cases, this mean value is used as the flow value of the mortar, which serves as the flow value for the test sample. To achieve this, additional water had to be added to the samples. As a result, the W/C ratio is no longer the same for all the samples. To visualize the consistency test, it was decided to present the test results for the sample of 100% untreated fRCA in Figure 4.9. From left to right, increasing amounts of water were added until the consistency reached a satisfactory level.

Table 4.9: The consistency of the fresh mortar test results

Sample	Water (gram)	Cement (gram)	W/C ratio	Diameter 1 (mm)	Diameter 2 (mm)	Mean (mm)	Deviation (%)
Ref 100% natural sand	742,5	1485	0,50	145	145	145	0
100% untreated fRCA	1063,6	1485	0,72	125	125	125	0
100% Acid-treated fRCA	325,4	496,3	0,66	139	135	137	1,46
100% milled fRCA	927,8	1485	0,62	141	117	129	9,3
75% milled fRCA	879,6	1492,2	0,59	113	118	115,5	2,16
50% milled fRCA	815,3	1487,4	0,55	117	119	118	0,85
25% milled fRCA	753,5	1485	0,51	127	128	127,5	0,39

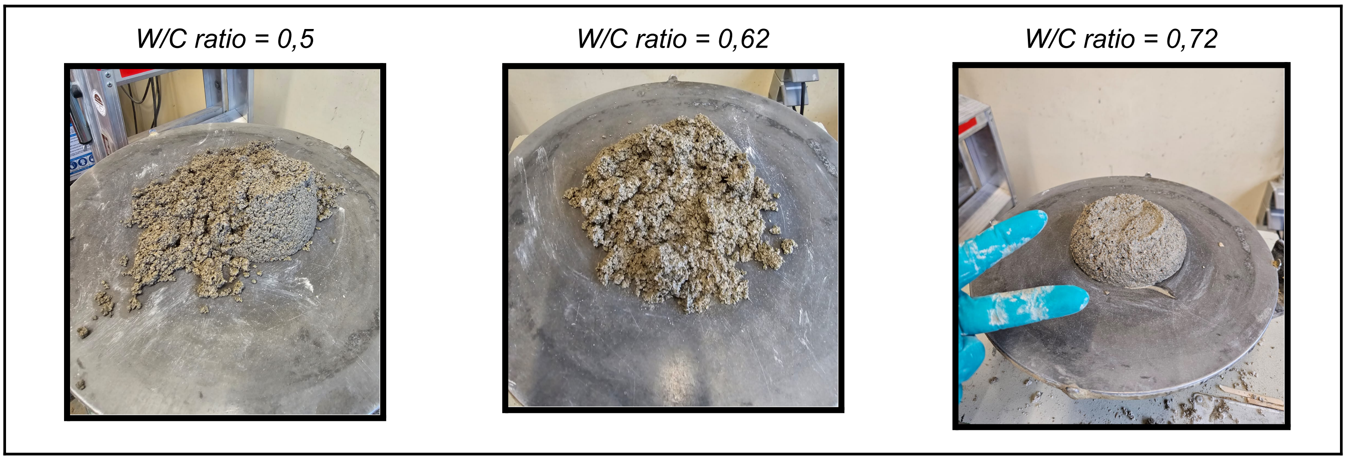


Figure 4.9:The consistency of 100% untreated fRCA with different W/C ratio’s.

As seen in Figure 4.9, the workability of the mortar was not sufficient without an increase in the W/C ratio. fRCA generally has a higher WA than NA, this leading to an increased in the need for water in the mix. The literature also discusses the total W/C ratio and the effective W/C ratio. The difference between them can be understood by examining the WA of the sand/aggregates used and the condition in which they are introduced. As long as the sand/aggregates are not water-saturated, they will absorb water from the mortar, reducing the amount of water available for the cement hydration reaction.
When fRCA added in a SSD condition, the WA has no impact on the W/C ratio during casting and, therefore, does not affect the workability of the mortar.
In the mixes, the sand/aggregates used were not in a SSD condition when added. With a higher WA and the assumption that fRCA has a higher WA than the sand used, the need for additional water can be explained. A higher W/C ratio typically results in a decrease in mortar strength, but in this case, it was necessary to achieve workability. The reduction in strength is less relevant here because fRCA has a higher WA than natural sand, which, over the time of the first day, leads to increased water absorption by the fRCA mixes, partially offsetting the increased W/C ratio. Furthermore, all samples are subsequently stored in a

curing room, where the samples are stored in a container filled with water, as also showed in Figure 4.8B.

4.4.3 Mortar flexural strength

The tests were conducted in accordance with NEN-EN 1015-11. The results for 2, 14, and 28 days after casting are displayed in Figures 4.9. The individual results are presented in Appendix C, along with the corresponding worksheets that were used.

In civil applications, the flexural strength has some significance, but the most critical factor is the compressive strength of the mortar. However, the mortar made with untreated fRCA appears to have a comparable flexural strength with the reference mortar. On the other hand, the flexural strength of the treated fRCA seems to be higher than that of both the fRCA and the reference sample, and that is positive.

This can be explained by two factors: surface texture and particle shape. fRCA has a higher surface roughness and a more angular shape than NS. The higher surface roughness of fRCA ensures better adhesion between fRCA particles and the cement matrix. This is because the surface roughness creates more contact points between the particles. More contact points result in better adhesion and higher tensile strength. Angular particles adhere better to each other than round particles due to their ability to interlock. Angular particles often have sharp edges and corners that interlock with the edges and corners of other particles. This leads also to a stronger connection and higher tensile strength.

What is noteworthy is that the flexural strength of the samples at 28 days has a lower average than that at 14 days (early strength). It is possible that due to the presence of fRCA, the hydration reaction of cement was already completed after 14 days. To provide more insights into this, an investigation into the chemical properties of fRCA is necessary. It can't be attributed to temperature, type of cement, or storage conditions, as all samples were stored under the same conditions, and the mix had the same ingredients. In any case, the samples appear to be stronger than the reference one.

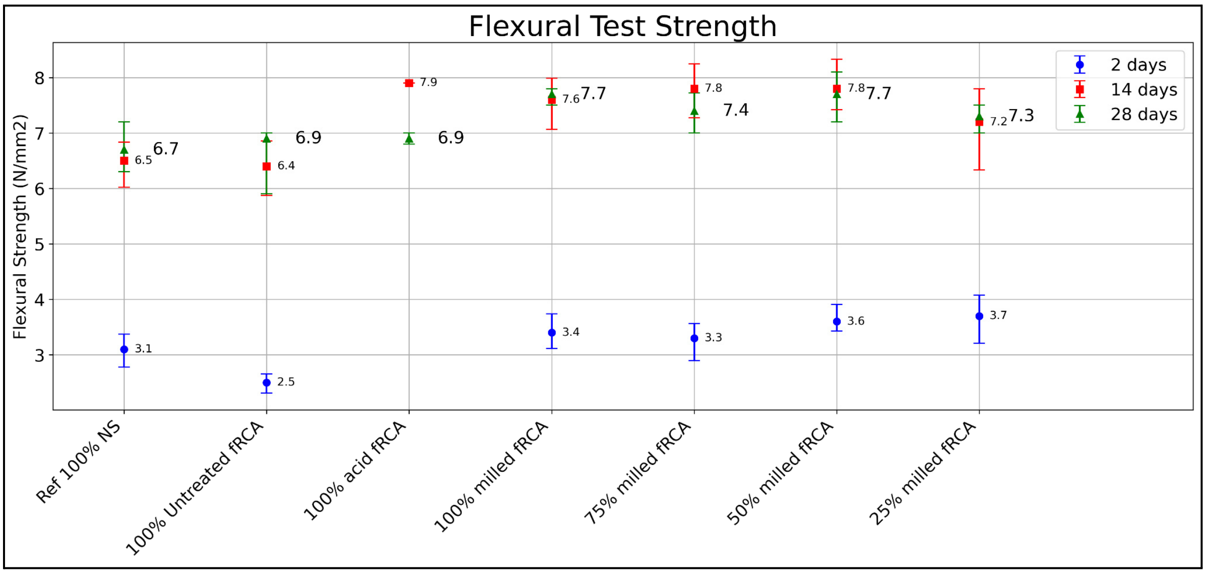


Figure 4.10: The Flexural Test Strength result.

4.4.4 Mortar compressive strength

The tests were conducted in accordance with NEN-EN 1015-11. The results for 2, 14, and 28 days after casting are displayed in Figures 4.9. The individual results are presented in Appendix C, along with the corresponding worksheets that were used.

The mortar produced using untreated fRCA exhibits the lowest compressive strength when compared to the other mortar specimens. In contrast, it is evident that the mortar made with milled fRCA or Acid-treated fRCA demonstrates higher strength than mortar with untreated fRCA. Nonetheless, both mortars do present lower strengths when compared to the reference mortar. The mortars produced using a mix of NS and milled fRCA and the reference mortar seem to exhibit higher compressive strength when compared to the mortar made with Acid-treated fRCA. However, the mortar made from untreated fRCA and milled fRCA exhibits lower compressive strength when compared to the mortar made with Acid-treated fRCA.

What is also noticeable from Figure 4.11 is that the variation in results of the early strength increases as the proportion of NS in the mix becomes higher. It is also evident that the strength develops more rapidly over time when a higher proportion of NS is used in the mix. The mortar with a composition of 25% milled fRCA and 75% NS appears to be the strongest.

The results of the 28-day strength test appear to vary significantly from the average. After comparing the results, it appears that the optimal amount of milled fRCA that can replace NS is 25%, but it can be increased to 100% depending on the requirements of the project and the quality of the fRCA. The milled fRCA samples appear to have lower early strength than the reference one, but after 28 days, their strength seems to become comparable to that of the reference. The strength of Acid-treated fRCA is somewhat disappointing after 28 days. It is somewhat stronger than untreated fRCA, but not strong enough to replace sand. The lower strength of the Acid one at 28 days compared to 14 days is likely due to the fact that only one sample was tested after 14 days, and this may not have been sufficient to accurately represent the variation in strength.

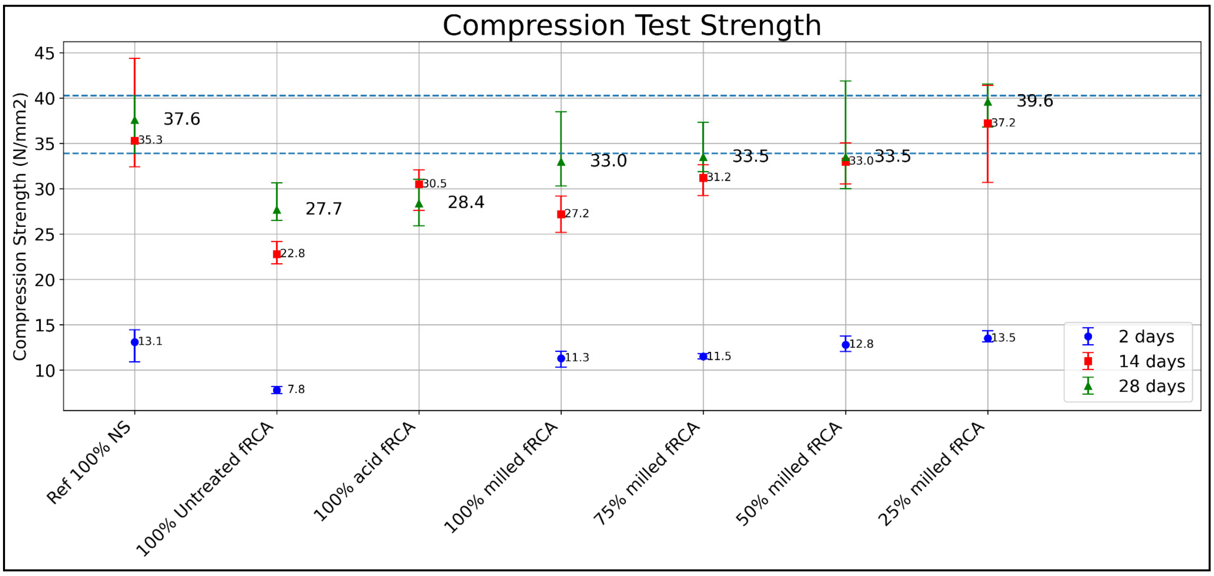


Figure 4.11:The Compression Test Strength result.

5. Conclusion and recommendations

This bachelor's thesis examines the use of Fine Recycled Concrete Aggregate (fRCA), produced by Heating air and classification system (HAS) from the Concrete to Cement Aggregate Technology (C2CA), in mortar mixes. This fRCA is a sustainable alternative for replacing natural sand. This research aims to characterize the properties of fRCA, determine optimal milling parameters, enhance the quality of fRCA through acid treatment and milling, investigate the impact of the water-cement (W/C) ratio on mortar workability, and assess the compressive and tensile strength of mortar with fRCA. The research has shown that fRCA can replace a portion of natural sand. Based on the findings of this thesis, the sub-questions of this research are first addressed, which leads to the main research question

Sub questions:

Which properties of fRCA affect the performance of concrete mixes?
Based on the literature review, the physical and chemical properties of fRCA, including particle size distribution, water absorption, moisture states, density, and chemical composition, collectively impact the performance of concrete mixes. These properties can influence workability, strength, durability, and the overall sustainability of concrete made with fRCA. Proper management and understanding of these properties are essential for achieving desired concrete performance when using fRCA.

How to improve the quality of fRCA?
Milling and acid washing can be effective methods for improving the quality of fRCA by removing the cementitious material. For milling, it appears that a mass ratio of fRCA to mass of steel balls used at 1:3 with 10 minutes of milling time works best for improving the quality of fRCA without creating an excess of fine fractions. Milling does not result in complete removal of cementitious material, whereas acid treatment, on the other hand, has succeeded in removing almost all the cementitious material.

How does the water to cement ratio and the amount of cement paste on fRCA surface influence the workability of concrete mixes?
The water-cement ratio and the amount of cement paste on fRCA surface have a significant impact on the workability of concrete mixes. A higher W/C ratio improves workability by making the mix more fluid for easy placement. The present cement paste on the fRCA surface can affect the strength negatively. Striking the right balance is crucial to ensure that the concrete is both workable and meets the required strength standards.

What is the optimum amount of fRCA to use to replace natural sand in a mortar mix?
The specific percentage of fRCA replacement for natural sand will vary. In many cases, fRCA can be used as a partial replacement for natural sand, with an optimum of 25% and can be extended to a replacement percentage to 100%, depending on the requirements of the project and the quality of the fRCA.

How sustainable is the new mortar mix made of fRCA?
Based on the literature review, mortar mixes made with fRCA can be considered as a sustainable choice due to their positive impact on natural resources. However, addressing the challenges related to material quality, standards, and cost considerations is essential to

further enhance the sustainability of these mixes. Proper quality control, more research, and the development of standards are important steps in maximizing the potential of fRCA in sustainable construction.

The practical sustainability assessments are out of the scope for this research, but the following was found through a simple calculation. The milling treatment used electricity, and for milling 1 kg of fRCA, 0.25 kW of power is used for 10 minutes, which is equivalent to 150 kJ. Based on the information from Cascade (appendix D), to extract 1 kg of sand from a river in the Netherlands, approximately 39.5 kJ of fossil energy and 5.5 kJ renewable energy is required. Extracting sand from the river will therefore use less energy than milling fRCA, but the scarcity of sand and the depletion of natural resources make milling fRCA to replace sand in mortar still sustainable.

Main question:

What is the best way to improve the properties of fRCA and use it in concrete mixes for civil engineering applications?

The answer to this question is not straightforward. It depends on the specific requirements of the project to determine the best way to improve the properties of fRCA and use it in civil engineering applications. fRCA (HAS fines) is commonly used in road construction in the form of roads foundation. However, fRCA also appears to be capable of partially replacing the natural sand (NS) used in other civil applications, such as construction applications. By milling or treating it with ACID, the quality of fRCA can be improved, making it possible to use fRCA as a replacement for NS in mortars with optimal substitution rate of NA with fRCA as 25%, with the possibility of an increase to 100%. The integration of fRCA in concrete holds potential for sustainability by reducing reliance on natural resources and curbing waste generated by the construction industry. Additionally, the flexural strength of concrete will also be improved.

It's important to consider that even after improving the quality of fRCA, its water absorption (WA) remains approximately 7 times greater than that of NS. This significantly affects the water required for the mix in which fRCA is used. More water is added to compensate for this, ensuring the reasonable workability of the mix. This extra needed water naturally impacts the water-cement ratio (W/C).

After conducting the 2, 14, and 28-day flexural and compressive strength tests on hardened mortar with different aggregate compositions, it appears that fRCA, whether subjected to acid treatment or milling, shows an improvement in flexural and compressive strength tests results.

In conclusion, this research concludes that it is possible to expand the use of fRCA in the civil engineering sector by improving the properties of fRCA through additional treatment after the HAS step in the C2CA technology, such as milling or acid treatment.

Recommendations:

This final project represents just the beginning of a journey toward a more sustainable future for the construction industry with more fRCA use. I hope that the findings in this research contribute to the ongoing development of innovative and sustainable solutions in civil engineering. It's clear that fRCA has the potential to replace NS, but further research and the development of standards and practices are needed to make this more accessible. The lack of established norms, standards, and practical experience may hinder the broader adoption of fRCA as a substitute for NS in various applications.

There are several possibilities for further research:

- In this research, the milling parameters were chosen based on the best matching PSD to the ACID-treated fRCA. Another interesting aspect to test is using the parameters that have a similar removal percentage, which would be a mass ratio of fRCA to the mass of steel balls at 1:4 with 10 minutes of milling time.
- Develop standards and guidelines for the use of fRCA in mortars and concrete.
- Conduct more research on the chemical properties of fRCA and milled fRCA.
- Improve the determination of the water absorption (WA) for milled fRCA and improve the water absorption of it.
- Perform long-term testing of mortars made with milled fRCA to assess their performance over extended periods.

These research opportunities would contribute to a better understanding of fRCA and its potential applications in civil engineering.

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Appendix A Water absorption and specific density

In this appendix, you will find the results for water absorption and specific density. Following that are some photos from the lab and the used worksheet.

Table A: Results Water absorption and specific density

Sand			
DESCRIPTION	SAMPLE NUMBER		
	I	II	
Weight of sample (g)	512,1	514,6	
Weight of Vessel + Sample + Water (g), A	1604,9	1615,5	
Weight of Vessel +Water (g), B	1291,2	1299,2	
Weight of Saturated & Surface Dry Sample (g), C	515,4	515	
Weight of Oven Dry Sample (g), D	510,4	511,4	Mean
Specific Gravity = [D/(C-(A-B))]	2,5305	2,5737	2,55
Apparent Specific Gravity = [D/(D-(A-B))]	2,5948	2,6212	2,61
Water Absorption, Percentage Dry Weight (%) = [(C-D)/D]x100,	0,979623824	0,703949941	0,84
Milled fRCA			
DESCRIPTION	SAMPLE NUMBER		
	I	II	
Weight of sample (g)	511,5	516,5	
Weight of Vessel + Sample + Water (g), A	1541,2	1508,7	
Weight of Vessel +Water (g), B	1242,5	1204,4	
Weight of Saturated & Surface Dry Sample (g), C	534,4	537,4	
Weight of Oven Dry Sample (g), D	499,9	503,2	Mean
Specific Gravity = [D/(C-(A-B))]	2,1209	2,1587	2,14
Apparent Specific Gravity = [D/(D-(A-B))]	2,4846	2,5299	2,51
Water Absorption, Percentage Dry Weight (%) = [(C-D)/D]x100,	6,901380276	6,796502385	6,85
fRCA			
DESCRIPTION	SAMPLE NUMBER		
	I	II	
Weight of sample (g)	505,9	500,5	
Weight of Vessel + Sample + Water (g), A	1524,7	1587,9	

Weight of Vessel +Water (g), B	1235,2	1297,9	Mean
Weight of Saturated & Surface Dry Sample (g), C	527	523,3	
Weight of Oven Dry Sample (g), D	492,6	489,4	
Specific Gravity = [D/(C-(A-B))]	2,0741	2,0977	2,09
Apparent Specific Gravity = [D/(D-(A-B))]	2,4254	2,4544	2,44
Water Absorption, Percentage Dry Weight (%) = [(C-D)/D]x100,	6,983353634	6,926849203	6,96

ACID fRCA

DESCRIPTION	SAMPLE NUMBER		
	I	II	
Weight of sample (g)	500,7	501,5	
Weight of Vessel + Sample + Water (g), A	1605,3	1518,1	
Weight of Vessel +Water (g), B	1298,8	1211,3	
Weight of Oven Dry Sample (g), D	496,8	497,5	Mean
Apparent Specific Gravity = [D/(D-(A-B))]	2,610615	2,60881	2,61

a) Materials in the Pycnometer,
The 2 in the left are sand, the 2 in the Middle are fRCA, and the 2 in the right are Milled fRCA

b) Materials left to dry till SSD condition
The 2 in the left are sand, the 2 in the Middle are Milled fRCA, and the 2 in the right are fRCA

c) Materials before the oven drying
The 2 in the top are sand, the 2 in the Middle are Milled fRCA, and the 2 in the bottom are fRCA

d) Materials after the oven drying
The 2 in the top are sand, the 2 in the Middle are Milled fRCA, and the 2 in the bottom are fRCA

Figure A:The water absorption and specific density process in photos from the lab.

<u>Determination of Specific Gravity & Water Absorption of fine Aggregates</u>

Standard: NEN-EN 1097-6

Required materials: Balance, thermostatically controlled oven, glass vessel, sieve, fine aggregate, pycnometer, air tight container, dry soft absorbent cloths, glass rod, wash bottle, filter paper, funnel,

Observation sheet

DESCRIPTION			SAMPLE NUMBER		
			I	II	III
1	Weight of sample (g)				
2	Weight of Vessel + Sample + Water (g), A				
3	Weight of Vessel +Water (g), B				
4	Weight of Saturated & Surface Dry Sample (g), C				
5	Weight of Oven Dry Sample (g), D				
6	Specific Gravity = [D/(C-(A-B))]				
7	Apparent Specific Gravity = [D/(D-(A-B))]				
8	Water Absorption, Percentage Dry Weight (%) = [(C-D)/D]x100,				
Average Values:		**Specific Gravity**			
		App. Specific Gravity			
		Water Absorption			

Procedure:

- Weigh 2 kg of fine aggregate in ssd condition
- Take 500g of the above sample for test (C) and place it into the pycnometer
- Fill the pycnometer partly with distilled water and stir with glass road to eliminate entrapped air and fill the pycnometer with distilled water to the mark. Shake it well to remove entrapped air and fill it completely with water using wash bottle
- Weigh the pycnometer along with its contents (A)
- Pour the contents of pycnometer into a tray, at the same time agitating (swirling). Rinse well with water to clean it
- Fill the pycnometer to the same level as before and weigh it (B)
- Decant the water from the tray into a beaker and then filter it. The solids retained on the filter paper are returned back to the fines in the tray
- Place the tray in the oven at 105 for 24 hrs
- Sample is removed from oven after 24 hrs and cool down in airtight container and weighed (D)
- Then Calculate the Specific Gravity, App. Specific Gravity and water of absorption

Specific gravity: The ratio of the mass of a unit volume of a material to the mass of the same volume of water at stated temperatures (dimensionless). i.e., It is the ratio of the weight of aggregate in air to the weight of equal volume of water displaced by saturated surface dry aggregate. $\rho = \frac{D}{C-(A-B)}$

Apparent Specific Gravity: The ratio of the weight in air of a unit volume of the impermeable portion of aggregate at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature. $\rho_{app} = \frac{D}{(D-(A-B))}$

Water Absorption: The increase in the weight of aggregates due to water in the pores of the material, but not including water adhering to the outside surface of particles expressed as a percentage of the dry weight.

Water absorption as percentage dry weight (%) $= \frac{(C-D)}{D} x100$

Appendix B The Consistence of fresh mortar

Table B: The consistency of the fresh mortar test results

Sample	Water (gram)	Cement (gram)	W/C ratio	Diameter 1 (mm)	Diameter 2 (mm)	Mean (mm)	Deviation (%)
Ref 100% natural sand	742,5	1485	0,50	145	145	145	0
100% untreated fRCA	1063,6	1485	0,72	125	125	125	0
100% Acid-treated fRCA	325,4	496,3	0,66	139	135	137	1,46
100% milled fRCA	927,8	1485	0,62	141	117	129	9,3
75% milled fRCA, 25% natural sand	879,6	1492,2	0,59	113	118	115,5	2,16
50% milled fRCA, 50% natural sand	815,3	1487,4	0,55	117	119	118	0,85
25% milled fRCA, 75% natural sand	753,5	1485	0,51	127	128	127,5	0,39

Determination of consistence of fresh mortar (by flow table)

Standard: NEN-EN 1015-13 **Date of tasting:**____________________________

Sample No:____

Preparation and storage conditions:____

Date of preparing :____

Results:

Specimen	Water (gram)	Cement (gram)	Diameter in direction 1 (mm)	Diameter in direction 2 (mm)
Ref 100% natural sand				
100% untreated fRCA				
100% Acid-treated fRCA				
100% milled fRCA				
75% milled fRCA, 25% natural sand				
50% milled fRCA, 50% natural sand				
25% milled fRCA, 75% natural sand				

Procedure

- Wipe the disc and the inner surface and edges of the mould clean with a damp cloth, let dry and lightly lubricate the surfaces with very low viscosity non-resin mineral oil
- If the table has not been used within the last 24 h, operate for ten revolutions before use.
- Place the mould centrally on the disc of the flow table and introduce the mortar in two layers, layer is compacted by at least 10 short strokes of the tamper to ensure uniform filling of the mold.
- Hold the mold firmly on the disk with one hand, while filling.
- Skim off the excess mortar with a palette knife and wipe the free part of the disk clean and dry
- Remove all water from around the bottom of the mold.
- After approximately 15 s, slowly raise the mold vertically and spread the mortar on the disc by shaking the flow table 15 times at a constant frequency of approximately one per second.
- Measure the diameter of the mortar in two directions perpendicular to each other using a caliper.
- Report results in mm to the nearest mm

Appendix C Flexural and Compressive Strength of hardened Mortar

In this appendix, you will find the results for Flexural and Compressive Strength. Following that is the used worksheet.

Table C.1: The Flexural Test Strength result after 2 days.

Specimen	Specimen Flexural Test max. Load (kN)	Specimen Flexural Test Strength (N/mm2)
Ref 100% natural sand		
1	1,203	2,819
2	1,456	3,412
3	1,363	3,195
Mean to the nearest 0,1 N/mm2		3,1
100% untreated fRCA		
1	1,073	2,516
2	1,123	2,631
3	0,975	2,284
Mean to the nearest 0,1 N/mm2		2,5
100% Acid-treated fRCA		
Not defined		
100% milled fRCA		
1	1,610	3,774
2	1,444	3,383
3	1,345	3,153
Mean to the nearest 0,1 N/mm2		3,4
25% NS & 75% milled fRCA		
1	1,481	3,47
2	1,246	2,921
3	1,530	3,586
Mean to the nearest 0,1 N/mm2		3,3
50% NS & 50% milled fRCA		
1	1,456	3,412
2	1,468	3,441
3	1,659	3,889
Mean to the nearest 0,1 N/mm2		3,6
75% NS & 25% milled fRCA		
1	1,622	3,803
2	1,733	4,063

3	1,363	3,195
Mean to the nearest 0,1 N/mm2		3,7

Table C.2: The Flexural Test Strength result after 14 days.

Specimen	Specimen Flexural Test max. Load (kN)	Specimen Flexural Test Strength (N/mm2)
Ref 100% natural sand		
1	2,930	6,868
2	2,850	6,68
3	2,585	6,058
Mean to the nearest 0,1 N/mm2		6,5
100% untreated fRCA		
1	2,943	6,897
2	2,523	5,914
3	2,776	6,505
Mean to the nearest 0,1 N/mm2		6,4
100% Acid-treated fRCA		
1	3,362	7,88
Mean to the nearest 0,1 N/mm2		7,9
100% milled fRCA		
1	3,307	7,75
2	3,411	7,996
3	3,017	7,07
Mean to the nearest 0,1 N/mm2		7,6
25% NS & 75% milled fRCA		
1	3,504	8,213
2	3,344	7,837
3	3,091	7,244
Mean to the nearest 0,1 N/mm2		7,8
50% NS & 50% milled fRCA		
1	3,257	7,634
2	3,159	7,403
3	3,547	8,314
Mean to the nearest 0,1 N/mm2		7,8
75% NS & 25% milled fRCA		
1	2,721	6,376
2	3,202	7,504
3	3,344	7,837
Mean to the nearest 0,1 N/mm2		7,2

Table C.3: The Flexural Test Strength result after 28 days.

Specimen	Specimen Flexural Test max. Load (kN)	Specimen Flexural Test Strength (N/mm2)
Ref 100% natural sand		
1	3,054	7,157
2	2,813	6,593
3	2,659	6,232
Mean to the nearest 0,1 N/mm2		6,7
100% untreated fRCA		
1	2,480	5,812
2	2,813	6,593
3	2,983	6,998
Mean to the nearest 0,1 N/mm2		6,5
100% Acid-treated fRCA		
1	2,973	6,969
2	2,899	6,796
3	2,906	6,81
Mean to the nearest 0,1 N/mm2		6,9
100% milled fRCA		
1	3,220	7,547
2	3,319	7,779
3	3,362	7,88
Mean to the nearest 0,1 N/mm2		7,7
25% NS & 75% milled fRCA		
1	3,196	7,490
2	3,282	7,692
3	2,955	6,925
Mean to the nearest 0,1 N/mm2		7,4
50% NS & 50% milled fRCA		
1	3,190	7,779
2	3,486	8,169
3	3,109	7,287
Mean to the nearest 0,1 N/mm2		7,7
75% NS & 25% milled fRCA		
1	2,986	6,998
2	3,183	7,461
3	3,220	7,547
Mean to the nearest 0,1 N/mm2		7,3

Table C.4: The Compressive Test Strength result after 2 days.

Specimen	Compression Test max. Load (N)	Compression Test Strength (N/mm2)
Ref 100% natural sand		
1.1	22,682	14,176
1.2	20,469	12,793
2.1	21,052	13,158
2.2	20,959	13,099
3.1	23,110	14,444
3.2	17,420	10,888
Mean to the nearest 0,1 N/mm2		13,1
100% untreated fRCA		
1.1	12,427	7,767
1.2	12,457	7,786
2.1	13,019	8,137
2.2	12,145	7,591
3.1	11,860	7,413
3.2	13,143	8,214
Mean to the nearest 0,1 N/mm2		7,8
100% Acid-treated fRCA		
Not defined		
100% milled fRCA		
1.1	16,496	10,310
1.2	19,329	12,081
2.1	17,686	11,054
2.2	18,492	11,558
3.1	17,897	11,186
3.2	18,672	11,670
Mean to the nearest 0,1 N/mm2		11,3
25% NS & 75% milled fRCA		
1.1	18,926	11,829
1.2	18,027	11,267

2.1	18,058	11,286
2.2	18,783	11,739
3.1	18,777	11,736
3.2	18,108	11,318
Mean to the nearest 0,1 N/mm2		11,5
50% NS & 50% milled fRCA		
1.1	20,048	12,530
1.2	19,304	12,065
2.1	21,238	13,274
2.2	20,593	12,871
3.1	22,031	13,769
3.2	19,756	12,348
Mean to the nearest 0,1 N/mm2		12,8
75% NS & 25% milled fRCA		
1.1	22,899	14,312
1.2	21,002	13,126
2.1	21,002	13,126
2.2	21,046	13,154
3.1	22,453	14,033
3.2	20,959	13,099
Mean to the nearest 0,1 N/mm2		13,5

Table C.5: The Compressive Test Strength result after 14 days.

Specimen	Compression Test max. Load (N)	Compression Test Strength (N/mm2)
Ref 100% natural sand		
1.1	52,345	32,716
1.2	71,020	44,388
2.1	49,365	30,853
2.2	51,924	32,453
3.1	58,339	36,462
3.2	56,085	35,053
Mean to the nearest 0,1 N/mm2		35,3
100% untreated fRCA		
1.1	34,829	21,760
1.2	36,228	22,643
2.1	36,827	23,017
2.2	36,077	22,548
3.1	38,718	24,199
3.2	36,619	22,887
Mean to the nearest 0,1 N/mm2		22,8

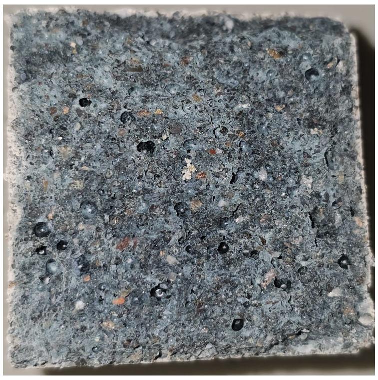
100% Acid-treated fRCA		
1.1	40,3	25,188
1.2	47,07	29,419
Mean to the nearest 0,1 N/mm2		27,3
100% milled fRCA		
1.1	51,317	27,591
1.2	50,085	31,030
2.1	51,196	31,997
2.2	46,106	28,816
3.1	44,145	32,073
3.2	49,648	31,303
Mean to the nearest 0,1 N/mm2		30,5
25% NS & 75% milled fRCA		
1.1	47,997	29,998
1.2	52,204	32,628
2.1	51,055	31,909
2.2	49,377	30,861
3.1	52,019	32,512
3.2	46,812	29,257
Mean to the nearest 0,1 N/mm2		31,2
50% NS & 50% milled fRCA		
1.1	51,534	32,209
1.2	55,402	34,626
2.1	50,162	31,351
2.2	56,161	35,101
3.1	55,000	34,378
3.2	48,924	30,577
Mean to the nearest 0,1 N/mm2		33,0
75% NS & 25% milled fRCA		
1.1	49,125	30,703
1.2	59,882	37,426
2.1	66,252	41,408
2.2	65,378	40,861
3.1	54,547	34,092
3.2	62,052	38,783
Mean to the nearest 0,1 N/mm2		37,2

Table C.6: The Compressive Test Strength result after 28 days.

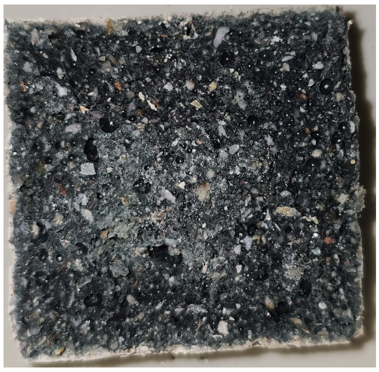
Specimen	Compression Test max. Load (N)	Compression Test Strength (N/mm2)
Ref 100% natural sand		
1.1	58,670	36,669
1.2	60,094	37,559
2.1	62,889	39,306
2.2	54,,254	33,909
3.1	64,402	40,251
3.2	60,470	37,794
Mean to the nearest 0,1 N/mm2		37,6
100% untreated fRCA		
1.1	42,387	26,492
1.2	42,828	26,768
2.1	45,482	26,551
2.2	45,331	28,332
3.1	49,006	30,629
3.2	43,528	27,205
Mean to the nearest 0,1 N/mm2		27,7
100% Acid-treated fRCA		
1.1	41,391	25,869
1.2	46,831	29,269
2.1	41,840	26,169
2.2	49,680	31,050
3.1	44,644	27,902
3.2	48,123	30,077
Mean to the nearest 0,1 N/mm2		28,4
100% milled fRCA		
1.1	61,606	38,504
1.2	54,234	33,896
2.1	52,600	32,875
2.2	49,579	30,987
3.1	48,508	30,317
3.2	50,251	31,407
Mean to the nearest 0,1 N/mm2		33,0
25% NS & 75% milled fRCA		
1.1	52,434	32,771
1.2	52,715	32,947
2.1	53,985	33,740
2.2	51,757	32,348
3.1	59,780	37,363

3.2	51,106	31,941
Mean to the nearest 0,1 N/mm2		33,5
50% NS & 50% milled fRCA		
1.1	47,972	29,982
1.2	58,491	36,557
2.1	67,056	41,910
2.2	57,272	35,795
3.1	55,255	34,534
3.2	55,210	34,507
Mean to the nearest 0,1 N/mm2		35,5
75% NS & 25% milled fRCA		
1.1	58,861	36,788
1.2	65,512	40,945
2.1	62,869	39,293
2.2	61,133	38,208
3.1	66,501	41,563
3.2	65,269	40,793
Mean to the nearest 0,1 N/mm2		39,6

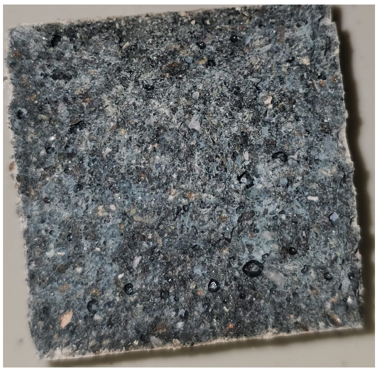
Ref 100% natural sand



100% untreated fRCA



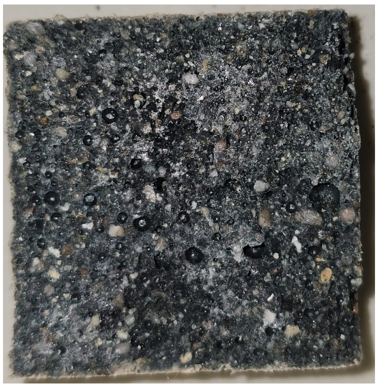
100% Acid-treated fRCA



100% milled fRCA

75% milled fRCA, 25% natural sand

50% milled fRCA, 50% natural san



25% milled fRCA, 75% natural sand

Figure C.1: The test pieces from the samples after 14 days.

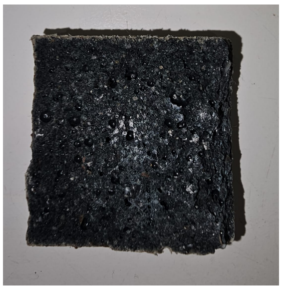
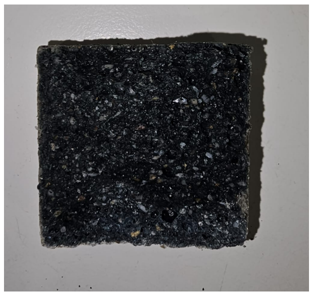
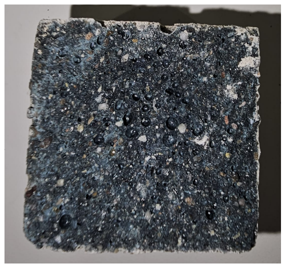
 Ref 100% natural sand	 100% untreated fRCA	 100% Acid-treated fRCA
 100% milled fRCA	 75% milled fRCA, 25% natural sand	 50% milled fRCA, 50% natural san
	 25% milled fRCA, 75% natural sand	

Figure C.2: The test pieces from the samples after 28 days.

Determination of flexural and compressive strength of hardened mortar

Standard: NEN-EN 1015-11 **Date of tasting:**____________________________

Sample No:____

Preparation and storage conditions:____

The flow value:____ **Age of Mortar:**_____________________ **Days**

Results:

Specimen	Flexural Test max. Load (N)	Flexural Test Strength (N/mm2)
1		
2		
3		
Mean to the nearest 0,1 N/mm2		

Specimen	Compression Test max. Load (N)	Compression Test Strength (N/mm2)
1.1		
1.2		
2.1		
2.2		
3.1		
3.2		
Mean to the nearest 0,1 N/mm2		

Procedure

1. Making Samples

1. Create three mortar specimens of 40 x 40 x 160 mm in size.
2. Cast the mortar into a mold and cover it with plastic film to prevent drying out.
3. Store the specimens for 24 hours at 20 ± 2 °C.
4. Test the specimens after 28 days. (in my case also 2 and 14 days)

2. Flexural Test

1. Wipe the bearing surfaces of the roller and the sides of the specimen clean with a clean cloth to remove any loose debris or other materials.
2. Place the test piece with one of its sides (the one cast against the steel of the mold) on the two supporting rollers spaced 100 mm apart.
3. Apply the load smoothly at a uniform rate within the range of 10 N/s to 50 N/s, causing failure within a period of 30 s to 90 s.
4. Record the maximum applied load in N. Return the broken specimen to the storage room and keep it there if necessary for compressive strength measurements.

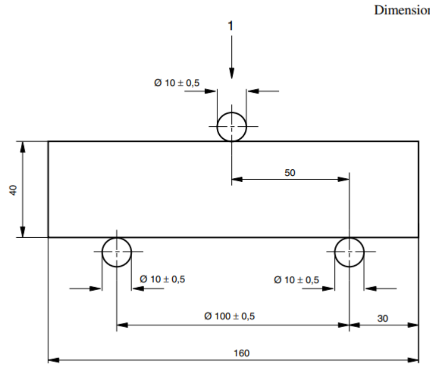
   Calculate the flexural strength, f, in N/mm² using the following equation:

   $$f = 1{,}5\frac{Fl}{bd^2}$$

   b and *d* (see 4.2) may be taken as the internal mould dimensions.

   Record the flexural strength of each specimen to the nearest 0,05 N/mm². Calculate the mean to the nearest 0,1 N/mm².
5.

Dimensions in millimetres



Key: 1 Load

3. Compression Test

1. Remove any loose grit or other material from the sides of the specimen as cast.
2. Wipe the bearing surface of the testing machine, and the bearing plates and jig, with a clean cloth
3. place the specimen in the machine in such a manner that the load is applied to one of its faces (which has been cast against the steel of the mould)
4. Arrange the prism so that the cast end is 16 mm ± 0,1 mm from the nearer edge of the platens or bearing plates
5. Position the measuring heads of the testing machine at the center of the specimens.
6. Apply the load smoothly and continuously increase it at a rate within the range of 50 N/s to 500 N/s, causing failure within a period of 30 to 90 seconds.
7. Record the maximum load applied, in N, during the test.
8. Calculate the strength as the maximum load carried by the specimen divided by its cross-sectional area.
9. Record the strength of each specimen to the nearest 0,05 N/mm2. Calculate the mean to the nearest 0,1 N/mm2.

Appendix D Environmental Product Declaration of Sand (0-4mm)

Environmental Product Declaration

volgens ISO 14025 en EN 15804

Deze declaratie is voor:

Zand 0-4 (industriezand)

van:

Cascade, vereniging van zand- en grindproducenten

program operator

Stichting MRPI®

uitgever

Stichting MRPI®

www.mrpi.nl

MRPI® registratie

1.1.00130.2020

datum eerste uitgifte

09-06-2020

datum deze uitgifte

09-06-2020

vervaldatum

09-06-2025

UITGEVER CERTIFICAAT
Stichting MRPI®
Kingsfordweg 151
1043GR
Amsterdam

PRODUCT
Zand 0-4 (industriezand)

MRPI® REGISTRATIE
1.1.00130.2020

BEDRIJFSINFORMATIE
Cascade, vereniging van zand- en grindproducenten
Postbus 110
5330 AC
Kerkdriel

DATUM UITGIFTE
09-06-2020

VERVALDATUM
09-06-2025

PRODUCT EENHEID/FUNCT. EENHEID
1 ton zand 0-4 (industriezand), in en nabij Nederland geproduceerd door Cascade-leden

TOEPASSINGSGEBIED CERTIFICAAT
Dit MRPI®-EPD certificaat is getoetst door **Lex Roes, Ecochain Technologies .**
De LCA studie is gedaan door **Martijn van Hövell, SGS Search Consultancy.**
Het certificaat is gebaseerd op een LCA-dossier volgens ISO14025 en NEN-EN15804+A1. Het is getoetst aan de hand van het 'EPD-MRPI® verification protocol May 2017.v3.1'. EPD's van bouwproducten zijn niet vergelijkbaar als ze niet voldoen aan NEN-EN15804+A1. Stoffen die voorkomen op de kandidatenlijst van SVHC's van het ECHA worden in dit certificaat gedeclareerd als ze de limiet voor registratie van die stof overschrijden.

AFBEELDING


BESCHRIJVING PRODUCT
Zand 0-4 - Dit is Industriezand met de meest voorkomende korrelgradering. Het omvat zowel zand van 0-7 mm toegepast voor beton als zand 0-2 vaak toegepast als metselzand.

MEER INFORMATIE
www.cascade-zandgrind.nl

BEWIJS VAN TOETSING
CEN norm EN15804 is de PCR[a]
Onafhankelijke toetsing van certificaat en dossier, volgens EN ISO 14025:2010: intern: extern: X
(Indien van toepassing) Onafhankelijke toetser: Lex Roes, Ecochain
[a] Product Category Rules [b] Facultatief voor B-to-B communicatie, verplicht voor B-to-C communicatie (zie EN ISO 14025: 2010,9.4).

UITGEBREIDE PRODUCT BESCHRIJVING

Zand en grind komen in grote hoeveelheden voor in de Nederlandse bodem, maar niet overal in dezelfde samenstelling en vaak in verschillende bodemlagen. De fijnere en grovere zand- en grindfracties zijn meestal gemengd in de bodem aanwezig. Dit mengsel, ook wel toutvenant genoemd, moet daarom eerst bewerkt worden (zeven en klasseren) voordat het als industriezand of grind als toeslagmateriaal kan dienen in beton en of voor andere toepassingen. Het productieproces is te verdelen in de volgende stappen:

A1 - Voorbereiding/afgraven deklaag: Werkzaamheden voorafgaand aan het winnen;
A1 - Winnen: Het gebruik van zuiger/ winwerktuig;
A2 - Transport: Transport van winlocatie naar verwerklocatie
A3 - Voorscheiden: Het scheiden in grove klassen van zand en grind;
A3 - Ophoogzand bewerken: Overige bewerkingen van ophoogzand;
A3 - Laden: Het gaat hierbij om laden voor transport;

COMPONENT (> 1%)	[kg / %]
Samenstelling vertrouwelijk	----

(*) > 1% van totale massa

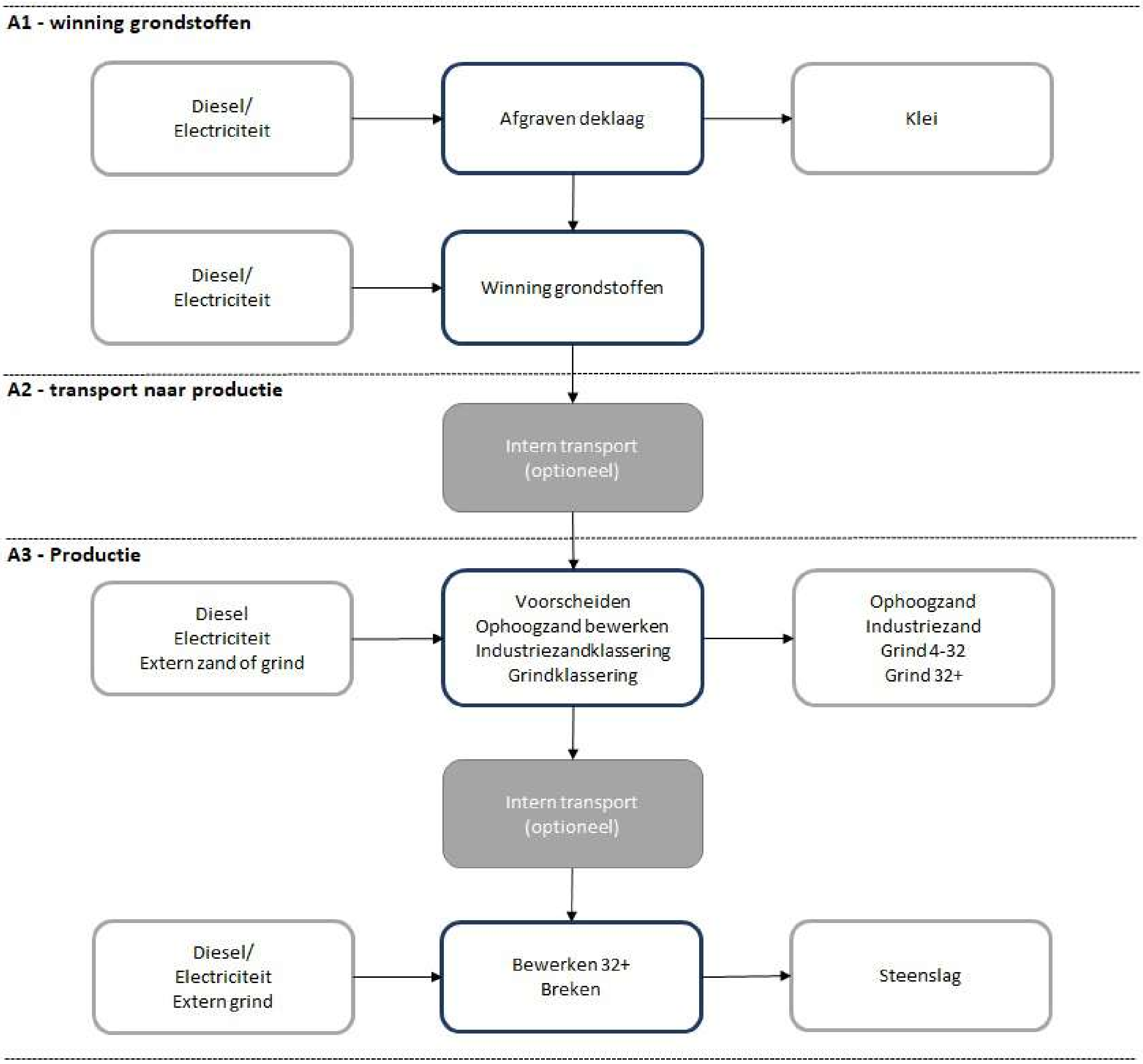
TOEPASSINGSGEBIED EN TYPE

Deze EPD is gebaseerd op een Cradle to Gate studie van zand- en grindproductie door leden van Cascade. De productielocaties die zijn geïnventariseerd voor deze studie zijn in en nabij Nederland. Het referentiejaar voor deze studie is 2018. Verder is deze studie opgesteld aan de hand van de Bepalingsmethode versie 3.0. (januari 2019) [1]. Dit document beschrijft een standaard werkwijze voor het opstellen van een LCA van een Nederlands bouwproduct, in aanvulling op de NEN-EN15804 [2], ISO 14040 [3], ISO 14044 [4] en ISO14025 [5]. Voor deze studie zijn referentieprocessen uit Ecoinvent 3.5 gebruikt en zijn berekeningen gemaakt in SimaPro 9.0.

PRODUCTIE FASE			CONSTRUCTIE PROCES FASE		GEBRUIKSFASE							EINDE LEVENSDUUR FASE				OPBRENGSTEN EN LASTEN BUITEN DE SYSTEMGRENZEN
Winning grondstoffen	Transport naar fabriek	Productie	Transport fabrieksspoort tot bouwplaats	Montage	Gebruik	Onderhoud	Reparatie	Vervanging	Renovatie	Energie gebruiksfase	Waterverbruik	Demontage-sloop	Transport	Afvalverwerking	Stort	Hergebruik- Terugwinning- Recycling- potentieel
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA

X = Module berekend

MNA = Module niet berekend



REPRESENTATIVITEIT

De LCA is gebaseerd op data voor identieke producten van verschillende producenten. Het milieuprofiel verschilt van producent tot producent meer dan 20% op meerdere milieueffectcategorieën. Dit heeft verscheidene oorzaken, waaronder de gebruikte energiemix (diesel, elektriciteit, duurzame energie) en procesverschillen die leiden tot verschillen in de gebruikte hoeveelheid energie. Er is gekozen om de productcategorie niet verder op te splitsen, omdat deze dan niet meer herkenbaar is voor de markt.

MILIEUBELASTING per functionele eenheid of producteenheid

	EENHEID	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
ADPE	kg Sb-eq.	3.54 E -6	8.71 E -8	1.99 E -6	5.61 E -6	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
ADPF	MJ	1.59 E +1	7.69 E -1	2.28 E +1	3.95 E +1	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
GWP	kg CO2-eq.	1.03 E +0	5.41 E -2	1.47 E +0	2.56 E +0	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
ODP	kg CFC11-eq.	1.02 E -7	9.04 E -9	1.76 E -7	2.87 E -7	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
POCP	kg ethene-eq.	5.99 E -4	3.01 E -5	8.74 E -4	1.50 E -3	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
AP	kg SO2-eq.	4.54 E -3	2.83 E -4	7.37 E -3	1.22 E -2	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
EP	kg (PO4)3--eq.	1.03 E -3	5.94 E -5	1.70 E -3	2.79 E -3	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
Indicatoren toxiciteiten (Nederlandse markt)																			
HTP	kg DCB-eq.	5.86 E -1	1.64 E -2	3.80 E -1	9.82 E -1	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
FAETP	kg DCB-eq.	6.42 E -3	4.40 E -4	6.24 E -3	1.31 E -2	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
MAETP	kg DCB-eq.	1.96 E +1	1.57 E +0	2.34 E +1	4.46 E +1	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
TETP	kg DCB-eq.	5.92 E -3	6.75 E -5	4.75 E -3	1.07 E -2	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
Milieu Kosten Indicator (Nederlandse markt)																			
MKI	Euro	1.37 E -1	6.14 E -3	1.59 E -1	3.02 E -1	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA

INA = Indicator niet berekend
ADPE = Uitputting van abiotische grondstoffen, excl. fossiele energiedragers
ADPF = Uitputting van fossiele energiedragers
GWP = Klimaatverandering
ODP = Ozonlaagaantasting
POCP = Photochemische oxidantvorming
AP = Verzuring
EP = Vermesting

HTP = humaan-toxicologische effecten
FAETP = Ecotoxicologische effecten, aquatisch (zoetwater)
MAETP = Ecotoxicologische effecten, aquatisch (zeewater)
TETP = Ecotoxicologische effecten, terrestrisch
MKI = Milieu Kosten Indicator

GRONDSTOF GEBRUIK per functionele eenheid of producteenheid

	EENHEID	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
PERE	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
PERM	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
PERT	MJ	2.39 E +0	1.42 E -2	3.13 E +0	5.54 E +0	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
PENRE	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
PENRM	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
PENRT	MJ	1.57 E +1	8.24 E -1	2.31 E +1	3.96 E +1	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
SM	kg	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
RSF	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
NRSF	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
FW	m3	7.55 E -3	1.56 E -4	3.93 E -3	1.16 E -2	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA

INA = Indicator niet berekend
PERE = Gebruik van hernieuwbare primaire energie exclusief hernieuwbare primaire energie gebruikt als materialen
PERM = Gebruik van hernieuwbare primaire energie gebruikt als materialen
PERT = Totaal gebruik van hernieuwbare primaire energie
PENRE = Gebruik van niet-hernieuwbare primaire energie exclusief niet hernieuwbare energie gebruikt als materialen
PENRM = Gebruik van niet-hernieuwbare primaire energie gebruikt als materialen
PENRT = Totaal gebruik van niet-hernieuwbare primaire energie
SM = Gebruik van secundaire materialen
RSF = Gebruik van hernieuwbare secundaire brandstoffen
NRSF = Gebruik van niet-hernieuwbare secundaire brandstoffen
FW = Netto gebruik van zoetwater

OUTPUT STROMEN EN AFVALCATEGORIËN per functionele eenheid of producteenheid

	EENHEID	A1	A2	A3	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
HWD	kg	9.87 E -5	5.71 E -6	1.46 E -4	2.51 E -4	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
NHWD	kg	9.91 E -2	2.36 E -2	5.05 E -2	1.73 E -1	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
RWD	kg	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
CRU	kg	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
MFR	kg	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
MER	kg	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
EEE	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA
ETE	MJ	0.00	0.00	0.00	0.00	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA	INA

INA = Indicator niet berekend
HWD = Gevaarlijk afval
NHWD = Niet gevaarlijk afval
RWD = Radioactief afval
CRU = Componenten voor hergebruik
MFR = Materiaal voor recycling
MER = Materiaal voor energie terugwinning
EEE = export van elektrische energie
ETE = export van thermische energie

SCENARIOS EN AANVULLENDE TECHNISCHE INFORMATIE

A1 Winning van grondstoffen

In deze module is het winnen van grondstoffen opgenomen.

A2 Transport van grondstoffen naar producent

Deze module omvat het transport van grondstoffen naar de producent. In het geval van zand en grind vindt verwerking vaak plaats op de locatie waar het gewonnen wordt. Vandaar is in veel gevallen transport in A2 niet van toepassing.

A3 Productie

In deze fase worden de verschillende fracties gescheiden en gereed gemaakt voor transport. Ook het laden van schepen of vrachtwagens is meegenomen in deze fase.

DECLARATIE VAN SVHC

Dit product stoot geen stoffen of gassen uit die voorkomen op de "Candidate List of Substances of Very High Concern for authorisation".

REFERENTIES

[1] Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken versie 3.0, SBK januari 2019.
[2] NEN-EN 1584 Duurzaamheid van bouwwerken - Milieuverklaringen van producten - Basisregels voor de productgroep bouwproducten.
[3] ISO, 2006. “Environmental management. Life cycle assessment - Principles and framework”. ISO 14040:2006;.
[4] ISO, 2006. “Environmental management. Life cycle assessment – Requirements and Guidelines”. ISO 14044:2006;.
[5] International Organization for Standardization, ISO/TR 14025, “Environmental labels and declarations – Type III environmental declarations”, ISO/TR 14025:2000;.

OPMERKINGEN

Deze EPD mag enkel gebruikt worden door Cascade leden.