'' The impact of recycled cement paste in the development of sustainable mortar''

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MSC THESIS

TU DELFT

DELFT 2020

Delft University of Technology

Master Thesis

" The impact of recycled cement paste in the development of sustainable mortar"

submitted for the degree of

Master of Science in

Environmental Engineering

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December 2020

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Acknowledgement

This thesis depicts the research project " The impact of recycled cement paste in the development of new green mortar". This research project is part of the TU Delft course CIE5060-09, carried out at TU DELFT concrete lab. This research is the last project to fulfil the graduation part of the Master (MSc) programme of Environmental Engineering at TU Delft. The goal of this research project is to investigate the effectiveness of the usage of recycled ultrafine particles from Construction and Demolition Waste in the field of mortar/concrete production, studying also the ecological and economic impacts from their usage. This can lead to a stimulation of sustainable opportunities.

My interest in Concrete section and the Recycling issues it brings with it, leaded me to the subject of Recycled cement paste and its impact. This research has been formed as a result of several meetings with Prof. Peter Rem and other members of the committee Dr Abraham Gebremariam, Dr Maarten Bakker and Dr Daan Schraven. Several sustainable issues regarding the usage of recycled ultrafine particles emerged that might be interesting to be investigated. The brainstorm sessions resulted in a problem statement in the field of the concrete/mortar production in the civil engineering sector. Next to this, it is was important the ecological and economic characteristics of the utilization of this new material to be studied. This project can investigate how “green’’ is this product.

For this report I would like to thank my graduation committee, consisting of the following members:

- Prof. Peter Rem;
- Dr Abraham Gebremariam;
- Dr Maarten Bakker;
- Dr Daan Schraven.

I would like to thank the members of the committee for the great input and relevant information they provided me for the content of the research. This input helped me to get affinity with the subject, to structure the research and to raise the quality of the mortars.

Last, but not least, I would like to note that the whole thesis was conducted during the covid-19 period. This situation with the coronavirus worldwide, has as a result some of the experiments to be postponed, forced me to reach some information only through literature and not doing all the measurements that I had in my mind. But through the measurements that had been done before, there some useful conclusions and forecast about the effectiveness of recycled ultrafine particles in concrete/mortar production.

Thanks to this course and this research, I obtained some great insights and knowledge for my professional career after education on this subject.

Christos D. Mentzinis

Delft, December 29th 2020

Abstract

Nowadays environmental issues like the depletion of the natural resources and the pollution of the environment have led many researchers to make new projects about the reuse of waste from construction and demolition again in concrete industry. Among available solutions are the partial replacement of cement with recycled ultrafine particles (RUP) and the reuse of recycled sand (RS) as substitute of natural sand in mortar/concrete mixtures. The aim of the present research is to investigate if the new mortar with recycled ultrafine particles can substitute the reference mortar made of virgin materials and to investigate the possible accompanying ecological and economic benefits. This will be demonstrated in terms of technical feasibility, ecology and economy of the new mortars.

For the investigation of the main target of this MSc thesis, it was important three different experiments to be conducted. The 1st and 2nd experiment included the partial substitution of cement with RUP in 5%,10% and 15% respectively. The only difference was the size of RUP. In the 1st experiment were used only RUP below 125 microns and in the 2nd experiment only milled RUP below 45 microns. The 3rd experiment was more complicated with the simultaneous presence of RUP below 125 microns and the total replacement of natural sand with recycled sand. The w/b ratio was constant for the first two experiments at 0,5, but the w/c was increased as the replacement ratio of RUP also increased for all the experiments. The results were excellent about the fresh workability of the mortars in all the experiments with higher values of slump in contrast to the reference one from virgin materials. But there were some problems about the mechanical properties and especially the compressive strengths of the new mortars. The usage of smaller RUP below 45 microns improve the mechanical properties of the mortars with the highlight of the higher values for all the mortars in the test of flexural strength in the measurement after 14 days. Generally, it seems that as the replacement ratio of RUP was increased, the compressive strength of the mortars was decreased. For the 3rd experiment, the results regarding the mechanical properties were not very satisfactory despite the compensation with extra water. The quantity of this water has a crucial role for future researches and additionally lower replacement ratio than 100% is suggested for recycled sand.

The next step was to reveal the possible ecological advantages from usage of this new mortar with recycled cement paste. For this investigation, an ecological analysis was conducted. This ecological analysis included in the first part a simulation in the lab experiments and in the second part a simulation in a conceptual recycling plant. The results are pleasant for the both cases regarding the GHG emissions and especially CO_2. Initially, in the lab experiments, 5 % substitution with RUP instead of cement particles leads to 5,1% reduction of CO_2 emissions, 10% substitution with RUP leads to 10,2% reduction of CO_2 emissions and 15 % substitution with RUP leads to 14,8% reduction of CO_2 emissions. Moreover, for the simulation of a conceptual recycling plant, the reuse of RUP in the mortar/concrete industry can lead to significant reduction of CO_2 and less air pollution. Especially for the scenario in this MSc thesis,

there is a potential environmental gain with total CO_2 offset of 70,75 ton/day from this conceptual recycling plant. Up-to-day, the calcination of limestone to produce cement contributes to the emission of carbon dioxide. But the usage of recycled cement paste can reduce this bad consequence.

The last step the investigation for the potential economic benefits from the reuse of the recycled materials and especially RUP in mortar/concrete industry. For this business case, an integration of Cost-Benefit Analysis with Cash-Flows was conducted for the previous conceptual recycling plant. According to this economic analysis, there are benefits from the creation of market for RUP, recycled sand and coarse aggregate like gravel and their demand as well as from the compensation by the European Union due to the reduction in CO_2 emissions in this innovative conceptual recycling plant. The results revealed that the NPV was 5.955.631€ >0 for forecast of 18 year-operation. This can lead to a great payback period of the investment of about 33 months without the calculation of the taxation inside and with the conceptual discount rate at 10%. It has great perspectives for circular economy, with less waste, reuse of materials, less consumption of natural resources and less carbon emissions.

In conclusion, although some technical drawbacks, the usage of RUP in new mortars instead of cement seems very satisfactory, and especially smaller RUP have beneficial effect to the mechanical properties of the mortar. Recycled sand is a material that needs more investigation about the appropriate parameters. The reuse of recycled materials and especially RUP contribute to some ecological advantages regarding the CO_2 emissions. Also, there are possibilities for economic benefits for recycling plants with RUP as targeted material in products leading to the potential model of circular economy. Finally, RUP and other recycled materials can be the basis for sustainable and green development. Hence, recycled cement paste has as an impact the development of sustainable mortar in this industry.

Chapter 1

Background and motivation

1.1 Introduction

Construction Waste are produced by building constructions and renovations from surplus material (excess supplies), damaged or broken material (thus unusable), cut-off pieces, processing waste (saw dust, metal spoils) dismantled shuttering, used-up tools and accessories, packaging and garbage during the use from people in the constructional areas (Tam et al., 2018) .

Demolition waste are results from demolition of built structures like bridges, roads etc. their complete removal or renovation. It also includes demolition debris caused due to natural disasters (earthquakes, hurricanes and tsunamis), civil conflicts, vandalism, explosions, fires, collapse of weak structures etc (Tam et al., 2018).

C&D waste is divided into five main fractions i.e. metal, concrete and mineral, wood, miscellaneous and unsorted mixed fractions. It could contain (Tam et al., 2018):

- Concrete;
- Bricks, tiles and ceramics;
- Glass;
- Wood;
- Plastic;
- Bituminous mixtures and tars;
- Soils (contaminated) and stones;
- Metals (ferrous & non-ferrous);
- Gypsum based materials (including plasterboard);
- Insulation materials (including asbestos);
- Chemicals (including solvents);
- Waste electronic and electrical equipment;
- Packaging materials;
- Hazardous substances: asbestos (found in insulation, roofs and tiles and fire-resistant sealing), lead based paints (found on roofs, tiles and electrical

cables), phenols (in resin-based coatings, adhesives and other materials), polychlorinated biphenyls (PCBs) (which can be found in joint sealing and flame-retardant paints/coats, as well as electrical items) and polycyclic aromatic hydrocarbons (PAHs) (frequently present in roofing felt and floorings).

Nowadays, the yearly production of construction and demolition waste (CDW) has increased, but only a small ratio is recycled for reuse in concrete and mortar constructions. The preservation of natural resources is very important. For this reason, a big quantity of these materials can be recycled into mortar/concrete. These construction and demolition waste contain most old concrete. Recycled concrete aggregates (RCA) are a mixture of aggregates and hardened cement paste (Zhao et al., 2015) .

Concrete is the material that is used mostly in construction field worldwide. The benefits from its use are low cost, availability of raw constituent materials, workability and its ability to be cast into many shapes, good fire resistance and durability. These advantages outnumber the disadvantages of the big energy consumption and pollution resulting from the manufacture of cement (calcination of limestone). According to some studies, it is believed that the need for concrete worldwide will reach around 18 billion tons per year by 2050. The extreme use of concrete manufacture increases the use of natural aggregates leads to an ecological imbalance and negative environmental consequences. The current situation with big consumption of the natural resources for concrete and cement manufacture is unsustainable (Gorjinia et al., 2014).

Some scientists reckon that there are five ways to reach the goal of the sustainability in the construction field:

- increase the use of supplementary cementitious materials;
- increase the use of recycled materials;
- improve durability;
- improve mechanical properties;
- reuse of water.

The increase of the usage of recycled materials assists the maintenance of the natural resources, landfill space and protect the environment (Gorjinia et al., 2014).

It is thought that the construction waste equal with the half of the total waste (Gorjinia et al., 2014). The solid waste from the construction areas seem to be good replacements for aggregate in structural concrete and mortars. It is believed that a concrete or a mortar manufactured of recycled aggregates meets the theoretical green requirements. These requirements include that these aggregates (Gorjinia et al., 2014):

- recycle and reduce natural resources and energy consumption;

- not influence the environment;
- lead to sustainable development.

The usage of Recycled Ultrafine Particles (RUP) instead of cement particles in concrete mixtures can (Mahieux, 2020):

- increase the recovery potential of concrete;
- be used as a substitute of usual addition such as limestone filler what would reduce quarrying of natural resources;
- reduce environmental impacts of concrete, since Portland cement is known as the most impacting constituent.

Obviously, there is a need for CDW management and reuse, which could lead to some ecological and economy benefits. The recycled cement paste produced by CDW process is the material that will be studied in this research. It could substitute at some percentage the cement in the concrete construction meeting the appropriate green requirements. It could also contribute to the sustainability of the planet and to the wishful circularity regarding the economy.

1.2 Scope

The scope is to study how efficient is to use the recycling materials such as ultrafine particles that are derived from C&D waste in mortar mixtures and consequently in concrete mixtures as well as their potential ecological and economic impacts. The substitution of virgin materials such as cement and natural sand with recycled ultrafine particles and recycled sand is obligatory in order to test their benefits in concrete production. For checking their effectiveness, it is essential to measure the workability and the mechanical properties of the new one mortars. Simultaneously, it is also significant to investigate the possible ecological and economic impacts and benefits from their reuse and especially from RUP in contrast to the usage of virgin materials and if they can lead to sustainable development.

1.3 Main objective and research questions

The main objective of this research is ***"to investigate if the new mortar with recycled ultrafine particles can substitute the reference mortar made of virgin materials and to investigate the possible accompanying ecological and economic***

benefits." Hence, according to the literature study and the objective above, the research questions to be answered in this thesis are formulated and stated below:

<u>1st research question:</u>

Is this new mortar feasible?

<u>2nd research question:</u>

Are there any ecological advantages from the usage of this new mortar?

<u>3rd research question:</u>

What are the expectations for possible economic benefits from the reuse of recycled ultrafine particles and recycled sand in mortar/concrete industry?

The Table 1.1 below depicts the main objective and the research questions of this MSc thesis.

Title	Objective-Question
Main Objective	*"To investigate if the new mortar with recycled ultrafine particles can substitute the reference mortar made of virgin materials and to investigate the possible accompanying ecological and economic benefits."*
1st research question	*Is this new mortar feasible?*
2nd research question	*Are there any ecological advantages from the usage of this new mortar?*
3rd research question	*What are the expectations for possible economic benefits from the reuse of recycled ultrafine particles and recycled sand in mortar/concrete industry?*

Table 1.1 Main objective and research questions of MSc thesis research

1.4 Methodology

In this part, there is an analysis about the methodology for the investigation of the three research questions of this MSc thesis, leading to the demonstration of the main objective.

The methodology for this research is:

<u>For the 1st research question: (Is this new mortar feasible?)</u>

- Experimental study

  - Assessment of the impact of using recycled ultrafine as cement replacement (or as an addition) in a new mortar mix. (1st experiment)
    → Impact of recycled ultrafine particles (RUP)
  - Evaluation of particle size of the recycled ultrafine material on the strength of mortar. (2nd experiment)
    → Impact of RUP particle size
  - Formulation of a new mortar recipe that incorporates recycled sand and recycled ultrafine particles. (3rd experiment)
    → Impact of recycled sand

  - Analysis of experiments results and discussion leading to conclusions regarding the technical part

<u>For the 2nd research question: (Are there any ecological advantages from the usage of this new mortar?)</u>

- Ecological analysis
- Conceptual recycling plant design in Netherlands
- Investigation for reduction of GHG emissions and especially of CO_2 based on the lab experiments and on the conceptual plant design from the substitution of cement with RUP
- Checking for potential sustainable and green development from the use of RUP and recycled sand instead of virgin materials
- Assessment of the ecological advantages

<u>For the 3rd research question: (What are the expectations for possible economic benefits from the reuse of recycled ultrafine particles and recycled sand in mortar/concrete industry?</u>

- Economic analysis
- Conceptual recycling plant design in Netherlands with recycled materials production

- ❖ Combination of the ecological advantages from the reuse of recycled materials with possible economic benefits
- ❖ Integration of Cost-Benefit Analysis and Cash-flow Analysis
- ❖ Estimation of the payback period of this kind of investment
- ❖ Checking for potential sustainable development and circular economy from the reuse of recycled materials in mortar/concrete production
- ❖ Assessment of economic benefits for the investment of the conceptual recycling plant in present and future

For this MSc thesis, it would be useful some expressions from the methodology part to be explained. In the introduction of Chapter 5: Ecological and economic analysis, there is an analysis for the definitions of terms *sustainable development, green development and circular economy* that will help to the better comprehension of 2nd and 3rd research questions and total research.

1.5 The outline of the MSc Thesis

The outline of this MSc research project is depicted in Figure 1.1

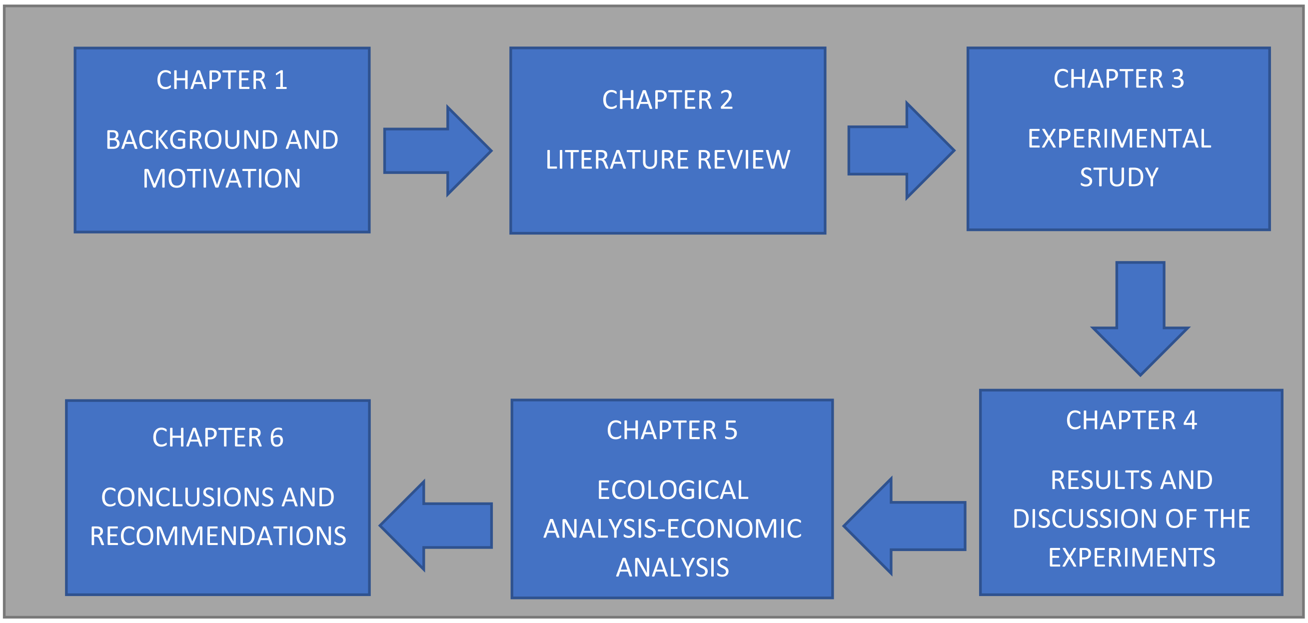

Figure 1.1 Outline of MSc thesis research

The chapter 1 includes the background and the motivation of this MSc thesis research. In this chapter the introduction, the scope, the main objective and research questions, the methodology and this outline of the research are analyzed. The second chapter indicates the literature review information regarding the technical part of the thesis. The chapter 3 covers the experimental study regarding the new mortar with recycled ultrafine particles in order to answer to the first research question about the technical feasibility. It includes the methods and the materials of the whole experimental phase. In the chapter 4, there are the results in graphs and the discussion of the experiments, in addition to their explanations. It is the outcome of the whole experimental study that was conducted. Chapter 5 deals with the ecological and economic analysis of this new idea. It answers to the expectations for possible ecological and economic benefits from usage of recycled ultrafine particles. It also investigates the potential sustainable and green development of the study. The last chapter is 6th one, which includes the conclusion and recommendations of the research. It includes the outcome of the whole MSc thesis and control if the initial objective "*investigate if the new mortar with recycled ultrafine particles can substitute the reference mortar made of virgin materials and investigate the possible accompanying ecological and economic benefits* " is satisfied or not.

1.6 Problems during MSc thesis

This MSc thesis was conducted between December 2019 and December 2020. The most important problem during this research, was the outbreak of the coronavirus-COVID19 which affected the experimental study and the days of measuring the mechanical properties of the mortars. Hence, it was impossible to make measurements in the age of 28 days of the mortars, because there was no access to the TU DELFT concrete lab, in which the experiment study took place. This led to a more theoretical approach of some parameters like w/c and w/b ratio and making some conclusions that are based on the 1-14 days of the experiments. So, the experimental phase acts like a kind of forecast for further research.

Chapter 2

Literature review

The literature review section focuses on the theoretical background on mortar and concrete manufacture and usage of C&D waste. It includes the history of Reuse of Construction and Demolition Waste (CDW), the benefits of Recycling Concrete Aggregate (RCA), legislation for the usage of Recycling Concrete Aggregate (RCA), the production and the treatment of Fine Recycle Concrete Aggregate (FRCA), the properties and effects of Fine Recycle Concrete Aggregate (FRCA), the chemical/mineralogical and microscopical analysis of Fine Recycle Concrete Aggregate (FRCA), the hydration kinetics (calorimetry) of Fine Recycle Concrete Aggregate (FRCA) and the technology for production and separation of Recycled Ultrafine Particles (RUP) from the fine particles including ADR and HAS systems.

2.1 Definitions about concrete industry

Mortar is a building material synthesized mainly of cement, which is regularly mixed with fine sands and water. Sometimes there is an addition of lime targeting the improvement of the durability of the product. The water addition to this mixture activates provoking to be hardened as concrete. Mortar is less strong than concrete and rarely is used as a sole building material. Usually, it is the sticky material that keeps together bricks, concrete block, stone, and other masonry materials (Beaulieu, 2020).

Concrete is a complete building material used for many structures. It is useful because it begins as a simple, dry mixture, then becomes a flexible, semi-liquid material with the ability to make formations into any mould or shape, and that finally dries into the hard material known as concrete. Adding metal reinforcement, such as wire mesh or rebar in concrete can reduce the cracking that can occur in solid concrete. Concrete is consisted of cement, sand, and gravel or other fine and coarse aggregate. The cement is activated when it mixed with the water (Beaulieu, 2020).

Cement is the binding element in both concrete and mortar. The composition includes mainly of limestone, clay, shells, and silica sand. These materials are crushed and combined with other ingredients and heated up at 1500 °C in clinker. Therefore, it is converted into a fine powder and used for mixing various cementitious building materials, including mortar and concrete. It is referred often as Portland cement because it is manufactured first in the island of Portland, off the coast of England and it is nowadays the most common type of cement used in constructional materials (Beaulieu, 2020).

2.2 History of Reuse of Constructional and Demolition Waste (CDW)

The issue regarding the study on management and recycling CDW has it first steps after the World War II, especially in the countries that most influenced by that. In 70s, some scientists stated that the usage of FRCAs decreased the workability of concrete mixture, but it did not affect the compressive strength of it. In 80s, it was believed that the fractions below 2mm must be removed when using RCA for concrete and mortar production. Scientists of that period stated that these fractions must be exploited for other reasons such as the production of alternative binders, the stabilization of soils, and as filtering material in water treatment plants. In 90s, some researchers reckoned that that the substitution natural aggregates (NA) with recycled concrete aggregates RCA) is feasible only with big particles bigger than 4mm due to the fact that the smaller ones influenced the workability and the strengths of concrete or mortar mixture. In middle of 90s, a researching working group reported that the usage of FRCAs must be further studied about its properties, standards, limits and performance on concrete and mortar mixtures (Evangelista & Brito, 2014).

There is a need of C&D waste recycling due to population growth, continuous industrial development, construction of infrastructure and house building activities, which produce big amounts of them. The natural resources are consumed and get limited by the constructional companies and the global aggregate production is increased rapidly every year. Many countries such as China, India, Indonesia, Malaysia, Thailand, Gulf States, Turkey, Russia, Brazil and Mexico have an increased demand on waste recycling. As the land for landfill gets limited and the aggregate demand increases, it is obligatory for both developed and developing countries to reuse CDW as alternative materials for useful purposes. The first country that associated with CDW recycling was Germany in 1984 followed by many parts of world like Australia, Western Europe and North America. In the beginning of the 21st century, Asia/Pacific, Russia and South American areas were thought to be the largest producers of aggregate as well as its sales, due to the increased construction activity, particularly in China, India, Indonesia, Malaysia, Thai- land, Gulf States, Turkey, Russia, Brazil and Mexico. China had crucial role in these activities, because alone accounts for half of all the new recycled aggregate demand worldwide during the five-year period of 2010–2015. The goal for environmentally conscience communities and enterprises is not only to recycle a large percentage of C&D waste, but to target for zero waste. This concept first emerged in California, USA, in 1975, zero waste plans have been adopted around the world, especially by local governments in Australia and New Zealand (Tam et al., 2018).

2.3 Legislation, Regulations and Suggestions for the usage of Recycling Concrete Aggregate (RCA)

There are some regulations and procedures for the ordinary usage of RCA. Many countries are preparing improvements on the existing ones that induct the acceptance criteria of RCA for concrete or mortar industry. Until now, the addition of them in this construction production is quite limited due to the current regulations. In late 90s, there was an agreement for the fine aggregates (FRCA) in construction production, but some years after, it was retracted. According to some regulations regarding the use of FRCA during the decade of 2000-2010, only Switzerland, Japan, Russia and U.S.A. allow 100 % its usage in non-reinforced (plain) concrete with restrictions in the classes of compressive strengths apart from American code. In Brazil according the regulation of 2005, FRCA can only be used for non-structural reasons. In the Netherlands according the regulation of 1994 allows 100 % the use of FRCA with maximum strength classes C20/25 and C40/50. In China and Spain, it is not allowed the use of FRCA for every purpose. According to some studies the last 10 years, it is indicated that is workable also to use FRCA for structural aspects and the quality of concrete is preserved in acceptance level. Some researchers stated that 100% FRCA can be utilized for exposure classes until XF4 guaranteed only a loss of 20% in compressive strength which is acceptable (Evangelista & Brito, 2014).

In European Union, the revised Waste Framework (Directive 2008/98/EC) set an ambitious target of achieving a 70% level of recovery for the recycling and reuse of non-hazardous C&D waste generated at constructional field by the year 2020. One way to fulfil this expectation is the recovery of cementitious materials, which represents the biggest amount in C&D waste. (more than one third of waste per year) (Mahieux, 2020). Unfortunately, it does not seem to achieve this goal. In countries with increased urbanisation like China, the production of CDW is huge. C&D waste could be demolished concrete structures, broken waste concrete, rejected concrete products on production line, bro- ken pavements and bricks from buildings. Therefore, they could be produced from demolition of concrete structures, airport runways, bridge supports, concrete roadbed or rejected concrete products on the production line, etc (Tam et al., 2018).

The actions and the measures that the countries should follow in order to reuse the C&D waste are (Tam et al., 2018):

- Prevention: information regarding the design of materials by considering their disposal and recycling and their environmental consequences.
- Separation: support recycling and decline disposal in landfill.
- Treatment: proposal regarding the introduction of a system based on permissions and legislation issued to those companies involved in the production of C&D waste. It is obligatory to indicate the produced waste amount, the adopted measure for treating it and its destination.
- Market: the market for C&D waste should be evolved to be profitable.

2.4 Technologies for recycling End-of Life concrete

There are two new technologies that are used for recycling End-of Life concrete. The first one is *ADR (Advanced Dry Recovery)* technology. It is a mechanical system of sorting and classifying wet CDW particles according to their particle size. It helps in the classification of the size fraction (0-12 mm) after demolition of End of Life (EoL) buildings. The crucial target of this technology is to separate the recycling materials above and below 4mm, creating the fine fraction 0-4mm (Gebremariam, Maio, & Lotfi, 2018). The second one technology is *Heating Air-Classification System (HAS).* The HAS technology is created to further expose the fine fraction aggregates (0-4mm). The fine recycled aggregates (0-4mm) is the input material for the HAS technology coming from the product streams of ADR. The crucial goal of this innovative technology is to separate the recycling materials above and below 0.25 mm, creating the ultrafine fraction 0-0.25mm (Gebremariam, Maio, & Lotfi, 2018). Hence, after the usage of HAS, there are two fractions below 4mm, the fine fraction 0.25-4mm and the ultrafine fraction 0-0,25. In the next paragraphs, the ADR and HAS technologies are analysed in more details.

2.4.1 Advanced Dry Recovery (ADR)

ADR (Advanced Dry Recovery) is a process that is conducted in two phases. Initially, a spinning rotor breaks the water bonds between the grains, after which small and light grains are separated from big and heavy grains by ballistic separation (Bakker, 2014). The input feed consists of particles 0-12 mm size. The water bond that is created by the moisture associated with the fine particles is broken due to the utilization of kinetic energy. It is widely known that after demolition of End of Life (EoL) buildings, the classification of the size fraction (0-12 mm) has the most problems because of the high moisture content of fraction. It is reported that the most moisture is associated the 0-1mm size fraction of the CDW, leading the fraction of 0-12 mm of recycling materials to be potential sticky. Hence, the possible removal of the 0-1mm fraction is a vital process in making better usage of the coarse fraction. The most important attribute of this technology is that the sustainability regarding to energy efficiency, it could be sustainable and affordable, compared to the conventional technologies developed earlier. The innovative characteristics of ADR are its ability to separate CDW aggregates independent of their moisture content and to be flexible with different input materials (e.g. limestone concrete wastes, lightweight concrete wastes) (Gebremariam, Maio, & Lotfi, 2018).

In the Figure 2.1 below, the sideview of ADR technology system is depicted according to Peter Rem (Rem, 2016). It shows the separation between the fractions above and below 4mm.

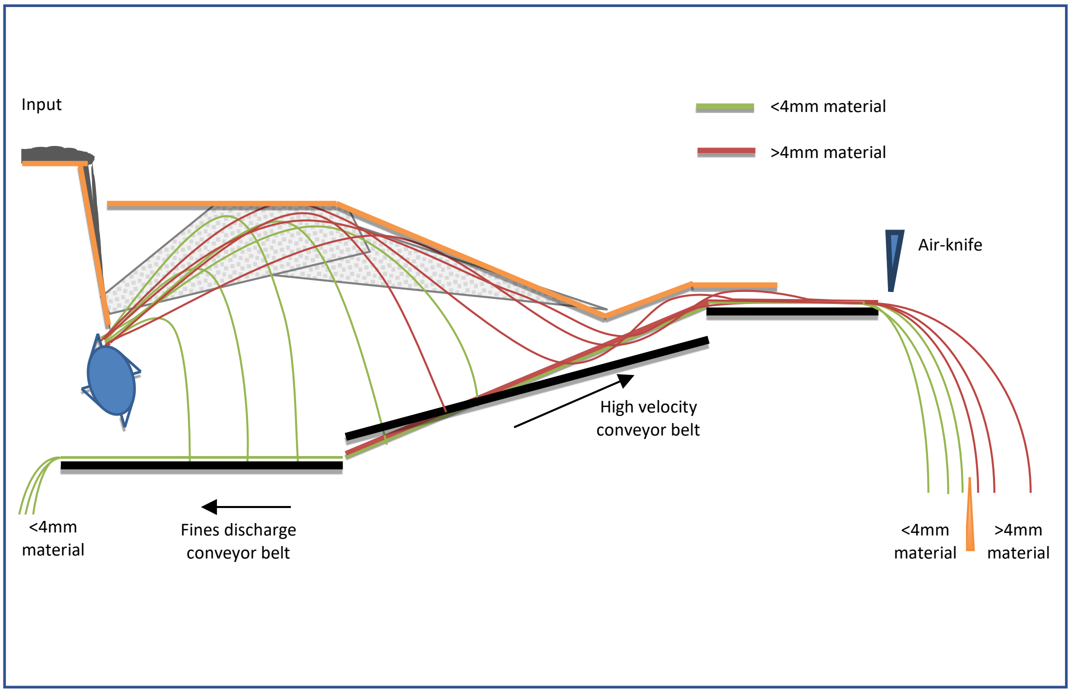

Figure 2.1 The sideview of ADR system (Rem, 2016)

In the first step, ADR compacts and rearranges the grains along the blade. The rotor blade has in this way connection with all grains and brings them to the horizontal velocity V=ωr (left side in Figure 2.2). Whether the material has enough moisture, some grains maybe slip to the rotor blade and rotate efficiently. After further rotation the velocity V_{hof} the rotor decreases and inertia forces grains to become airborne (right side in Figure 2.2). Because of the differences in initial impact, velocity ω_r and grains diverge in a fan, rather than following a straight horizontal line. The different trajectories pull the grains further separately and break the remaining water bonds. At sorting the water can make small free water droplets, but most of the moisture will remain adhered to the free particles (Bakker, 2014).

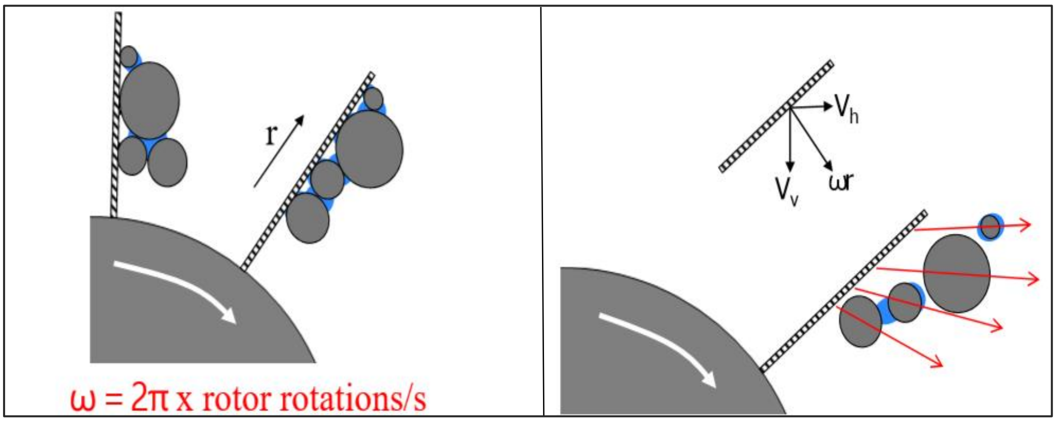

Figure 2.2 Closeup of the grain-motor interface (Bakker, 2014)

In the next step, a grain is subjected to air drag Fad= CwA0.5ρV^2. Due to the drag, there is a reduction of the grain kinetic energy 0.5m$V^2$and an increase of steeper trajectory. The larger the drag, the closer to the rotor the grain will drop onto the conveyor belt.

The main features of the ballistic separation are (Bakker, 2014):

- small grains have relatively larger surface-to-volume ratio (A/V) than large grains, thus they lose kinetic proportionally faster;
- As kinetic energy is proportional to mass, low-density and small grains have proportionally less kinetic energy;
- large and heavy grains travel further.

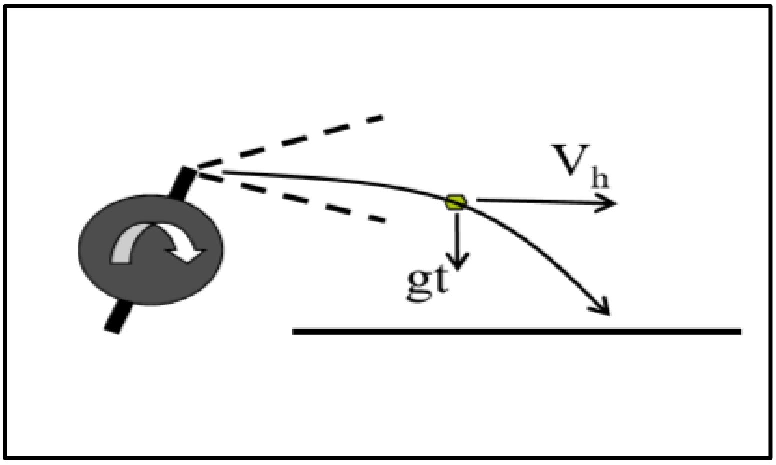

Figure 2.3 Dynamics of the ADR motor projectile (Bakker, 2014)

2.4.2 Heating Air-Classification System (HAS)

The Heating Air-Classification System (HAS) is created for separating the ultrafine fraction below 0.25mm from the fine fraction. This technology exposes the fine fraction aggregates (0-4mm) into a hot gas, targeting to remove the associated moisture. It can destroy undesirable CDW contaminants like wood and plastics by burning them out. The final products are clean sand and hardened cement paste. The fine recycled aggregates (0-4mm) that is coming from the product streams of ADR, acts as the input material for the HAS technology. The interaction between particle and gas system in a fluidized-type reactor contributes to this process, because the air in this reactor is used to transfer the heat and simultaneously classifies Eol concrete aggregates depending on their particle size (Gebremariam, Maio, & Lotfi, 2018). There are two goals-benefits from this heating. The first one is to remove the moisture and the second one is to activate the surface of ultrafine aggregates which mostly contains hydrated cement. The design of heating system allows maximum contact between air-particle system. Hence, while the ultrafine particles are pulled by the air flow, the heavier (fine) are collected at the bucket of HAS. If there is any adhesion of cement paste particles on the surface of the aggregates, the further exposure of these fine aggregates into autogenous milling could be a good solution for cleaning this aggregates surface (Gebremariam, Maio, & Lotfi, 2018).

The gravitational-counterflow zone is the main attribute of HAS technology, in which the classifier is designed around a rising air flow inside a vertical chamber. The main operation in this system is that the aggregate particles drop from the top of chamber and the drag force is activated in the opposite direction to gravity. Therefore, the classification occurs where the drag force is larger than gravity. Furthermore, according to Figure 2.4, the recycled ultrafine particles will be carried out by air flow whereas the fine particles will move downwards.

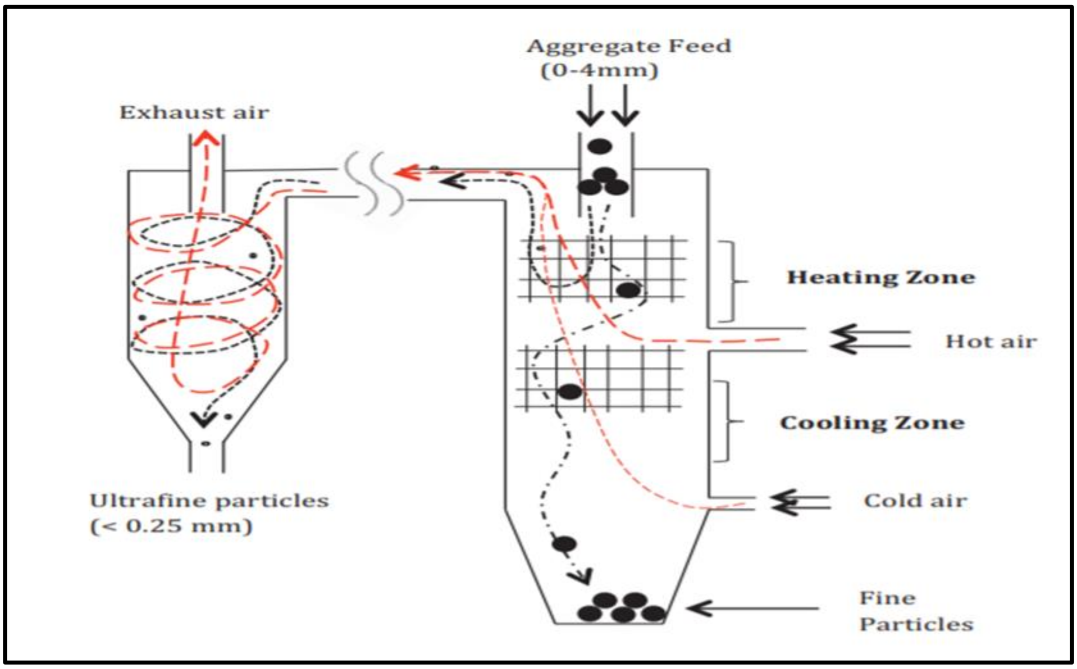

Figure 2.4 Cross section of the HAS (Gebremariam, Maio, & Lotfi, 2018)

The unique feature of HAS system is the presence of heating and cooling zones at the vertical chamber, something totally different from the technology in conventional air classifiers. There is enough residence time of CDW aggregates inside HAS for successful heat/mass transfer between wet aggregate and the hot gas. This time is also enough for wooden and plastic waste that come along with CDW to get burned at the heating zone. The features of fine aggregates and ultrafine particles after the thermal treatment by the HAS technology could be presented. The process of autonomous milling is capable of detach the hardened cement paste from the surface of fine aggregates (0.25- 4mm). The major composition of recycled ultrafine particles is hardened cement. Hence, they contain large amount of CaO, in contrast to fine fraction (0.25- 4mm) that contains α-quartz (sand). As it mentioned above, the wet and contaminated air-knife fraction (0-4mm) which was processed by ADR, is further treated by HAS for production of cleaner and drier recycled fine aggregates and ultrafine particles. Obviously, recycled fine aggregates have lower bulk and particle density compared to the fine natural aggregate (FNA). Hence, they absorb more water than the fine natural aggregate. This is a crucial drawback of recycled fine aggregate in contradiction to the natural fine aggregate (Gebremariam, Maio, & Lotfi, 2018).

In the market, the combination of the dehydrated cement paste, clinkers and gypsum can successfully lead to a new cement product. There is a recycling option for waste concrete and cement, which is beneficial for a sustainable development of construction industry. There is a possible conservation of natural resources and fuels as well as less emission of greenhouse gases. Hence, the environmental footprint is better with the utilization of HAS and the separation between the cement paste and the sand fraction (Gebremariam, Maio, & Lotfi, 2018).

2.5 Production and treatment of Fine Recycle Concrete Aggregate (FRCA)

The available technology for producing recycled aggregate from CDW by means of mechanical crushing is relatively cheap and easy operated. The process of converting C&D waste to recycled aggregate can be fulfilled in all countries, both in the developed and developing countries. The two categories of plants for processing C&D waste are stationary and mobile. The same processes that take place in both the plants to separate the contaminants from bulk material and to reach a useful grading are (Tam et al., 2018):

- Separation
- Crushing
- Screening
- Separation of ferrous elements
- Decontamination and removal of impurities (i.e. wood, paper, plastics)

One by-product of CDW crushing are FRCAs, which are highly contaminated. The Recycled Ultrafine Particles (RUP) belong to FCRA, but they are the particles with the smaller size in this aggregate. Hence, it is vital these contaminants to be screened during the production of CDW. The source and the comminution procedure of the CDW has great importance for the quality of the FCRAs. Separation of CDW is more efficient for higher speeds and it can be done using both density and magnetism (Evangelista & Brito, 2014).

The particle density and loose bulk density of FRCA are lower than those of fine natural aggregate (FNA). The main reason for this attribute is that the water absorption of FRA is higher than this of FNA, provoking this difference to the density. According to some studies from concrete plants for FRCAs characteristics, the water absorption can reach to a peak of 12 %, obtained particle density value is calculated for many cases more than 2.50 kg/dm^3 for hydrated mixtures and more than 2 kg/dm^3 for oven-dry particle densities (Evangelista & Brito, 2014).

The most important problem regarding the production of FRCA and the finer particles (ultrafine particles) is that these fine particles have high porosity; hence, they need extra water in the mixing during concrete/mortar manufacturing. Nevertheless, this situation does not affect the concrete/mortar performance negatively because a part of the mixing water that used for cement hydration will be absorbed by the FRCA, it could affect the dynamic mixing process, leading to the release of part of water into the paste affecting the w/c ratio. Some studies indicated that the pre-wetting of FRCA in concrete/mortar manufacturing to be partially saturated had as a result more homogenous paste interface than those with saturated FRCA. Other scientists believe that the addition of cement as last material in the mixer, it could increase the effectiveness of mixing with FRCA (Evangelista & Brito, 2014).

2.6 Properties and effects of Coarse Recycle Concrete Aggregate (CRCA) and Fine Recycle Concrete Aggregate (FRCA)

Mortar and hardened cement paste are principally the materials of the fine fraction (FRCA) of the total recycled aggregates. This fine fraction demands a large water quantity which makes it more difficult to recycle into concrete and mortar compared to coarser concrete aggregates. Some researches until now, indicated that as the replacement percentage ratio of FRCA enhanced, the properties of concrete are reduced (Zhao et al., 2015).

Moreover, the saturation state of recycled aggregate also affects the properties of concrete for a specific replacement percentage. According to some studies, the compressive strength is higher for oven dried coarse recycled concrete aggregates (CRCA) than that with saturated surface dried CRCA. Nevertheless, the role and the effect of recycled sand on mortars has not been systemically investigated yet. Probably, mortar constructed with FRCA has a lower strength and less durability than the natural sand-composed mortar, like concrete. As the percentage of FRCA increases, the compressive strength of mortar is reduced. Some scientists believe that the replacement of 30 % of FRCA do not affect the mechanical properties of mortars, but other disagree with this statement due to the higher water absorption of the recycled sand. According to some other studies, the concrete and mortars with recycled aggregate has less compressive strength in contrast to the natural aggregate (NA) ones. This is a result of the high-water absorption capacity of recycled aggregate and the lack of bonding between it and cement matrix. The quantity of the FRCA in the mixture of concrete or mortar affect its quality. Nevertheless, some reports indicate that RCA can be used in high strength, high performance and durable concretes (Gorjinia et al., 2014). The properties of mortars include fresh properties (slump) and mechanical properties (compressive strength and flexural strength) (Zhao et al., 2015).

According to some studies on properties of mortars, there are some useful results (Zhao et al., 2015).

- The dried recycled sand has higher slump than the mortars with saturated recycled sand. This happens because of the higher free water in the beginning of the experiment in the mortars constructed with dried recycled sand independent of w/c ratio. This leads to the conclusion that that the absorption of water by dried FRCA in the mortar is lower than this by saturated ones due to the kinetics of absorption.
- The compressive strengths of mortars that contained dried FRCA are better than that those with saturated aggregates independent of w/c ratio.
- The fresh density of mortar is reduced, when the natural sand is replaced with recycled sand because the recycled sand has lower density. As the percentage of replacement with FRCA enhances, the compressive strengths decrease in an almost linear way.

To improve the quality of a concrete containing RCA, factors such as micro cracks in RCA after the crushing process, high water absorption, smaller specific gravity of RCA as well as a possible reduction in quality and durability should be principally considered. One good opportunity is the substitution of natural sand with recycled sand up to 20%. Until today, it is believed that the compressive strength of a mortar decreases as the natural sand is substituted with recycled sand independent of the age of the mortar. Some experiments have shown that it is totally feasible to replace normal coarse aggregate with coarse RCA. The results of many studies have revealed that the compressive strength of RCA concrete is reduced as the quantity of RCA increases, this is because of the existence of the cement paste residue in the aggregate particles. The drying shrinkage strain of RCA concrete may range from 20% to 70% more than the normal concrete, which, together with the 100% replacement of NA with RCA, might reach up to 263% (Gorjinia et al., 2014).

The fresh-state properties of RCA are affected of the presence of FRCA due to their higher angularity and water absorptivity in contrast to natural aggregates. FRCA seem to have higher air content and lower density. Some scientists believe that these fine particles act as a lubricant leading to lower w/c ratio and slump loss. In order to get the same workability, one scenario could be to mix wet and dry FRCA particles. The reduction of compressive strength seems to be the most crucial problem regarding the workability. In all cases the increase of w/c ratio and the addition of cement could help the workability and the slump loss. The use of only non-saturated recycled aggregates in concrete/mortar increases their early age workability, which falls substantially as time goes by because of the RCA’s water absorption. It seems obligatory to add approximately 15% extra mixing water when FRCA, such as recycled sand, used (Evangelista & Brito, 2014).

Compressive strength is one parameter that it needs a further research for FRCA and RUP concretes/mortars. Based on some studies, the addition of coarse and fine RCA reduces the average compressive strength by between 8 and 60% in contrast to natural materials. Other studies with varied replacement ratio of FRA (0, 20, 50 and 100%) indicated that compressive strength losses ranged from 18 to 39%, depending on the mix. Other scientists found that the compressive strength loss varied from 43 to 54% for dry-mix shotcrete, between 40 and 45% for wet-mix shotcrete and between 41 and 56% for moulded concrete and their compressive strength evolved with age in a similar way to that made of natural material. The addition of superplasticizer in the mixing with FRCA seems to improve the compressive strength with an insignificant loss (Evangelista & Brito, 2014). Compressive strength of concrete included RCA can be up to 40 % lower, dependent on the substitution level and the quality and origin of aggregates. Many parameters of durability are affected by the presence of RCA. There are some control operations to help to solve these effects such as adjusting the mix design (e.g. chemical admixtures content) or by using more efficient crushing processes resulting in 'clean' recycled aggregate. Also, carbonation of RCA before the usage could control the problems (Mahieux, 2020). These side-effects can be controlled by adjusting the mix design (e.g. chemical admixtures content) or by using more efficient crushing processes resulting in 'clean' recycled aggregates. Other methods, such as carbonation of RCA prior to their use, offer also solutions to overcome these issues. With thermal treatment the recycled fines can also activate binders such as blast furnace slag or fly ash. Another theory is that recycled concrete fines, even without thermal treatment, can substitute the cement without loss of if the replacement rate is lower than 20 % (Mahieux, 2020). Furthermore, another scientist believes that the reduction of the cement content in a mortar can be efficient with the presence of crushed concrete fines in the sand. In many cases, sieved particles at 80 μm used, because this size is the most suitable for mineral additions (Mahieux, 2020).

Tensile strength (splitting and flexural) also plays an important role in the performance of the structures and construction industry. Scientific reports indicated reductions up to 26% in flexural tensile strength when both coarse and fine aggregates are totally replaced depend on the use of plasticisers and the pre-wetting of aggregates. Also, it depends on w/c ratio and the replacement ratio. Mixtures with lower w/c ratios (up to 0.47), have an increase in strength with increasing replacement ratio, while for higher w/c ratios the opposite occurs, with a decrease in strength. Compaction problems and insufficient mixing water can lead to this previous result. The splitting tensile strength is decreased, as the replacement ratio of FNA by FRA is increased (Evangelista & Brito, 2014).

2.7 Chemical/mineralogical and microscopic analysis of Fine Recycle Concrete Aggregate (FRCA)

According to some researches until 2012 about the fine/ultrafine recycled particles below 90 μm fraction of CDW that could be used for cement substitution purposes, the majority was SiO_2 that reached at 75 %, followed by CaO, Al_2O_3 and Fe_2O_3 contents in smaller rates. Also, these recycled fine parts had 0.73 m^2/g Blaine specific surface, higher than that of cement and fly ashes (Evangelista & Brito, 2014).

Regarding the microscopic analysis, the ratio between length and width of the particles (L/W) of the natural aggregates was almost the same with this of FRCA. But the sphericity of the particles differs much more, and the ones of FRCA had greater angularity. Something that explains the worse workability for the same w/c ratio. This attribute of greater angularity is provoked by the brittleness of the recycled materials and their crushing process, connected with open pores on the surface of the FRCA, leading to an increase to their specific surface. According to some thermogravimetric and differential calorimetric analyses, the mortars of FRCA have similar characteristics with the mortars containing natural aggregates, with the only difference that the latter have lower mass losses due to the presence of stone in their composition (Evangelista & Brito, 2014).

2.8 Hydration kinetics (calorimetry) of Fine Recycle Concrete Aggregate (FRCA)

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The heat emitted by hydration of cement is correlated with subtracting the heat from FRCA from the total heat according to the following formula (Mahieux, 2020):

$Q_c = Q_{tot} - Q_{FRCA}$

- Q_{tot} is the total heat that can be obtained from calorimetry tests;
- Q_{FRCA} is the heat that is released potentially from FRCA;
- Q_c is the difference between Q_{tot} and Q_{FRCA} called as the heat that emitted by hydration of cement;
- Q_c is expressed in J per g of cement and these values can depict that the heat release level enhances with the cement replacement.

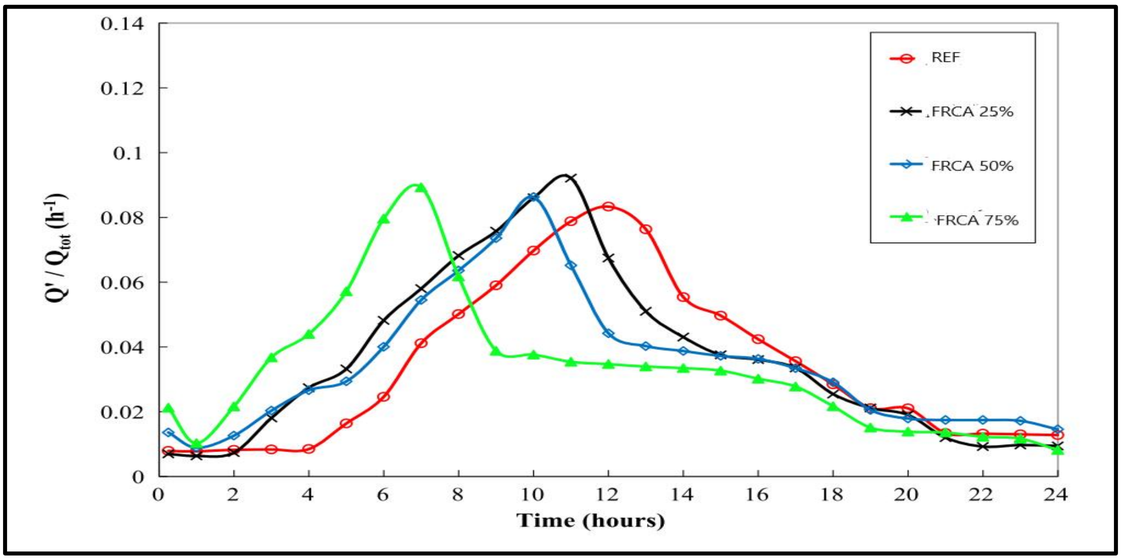

Figure 2.5 Rate of heat evolution of mortars with FRCA

In the Figure 2.5 above, according to Mahieux, the calorimetry tests show that FRCA play an important role in cement hydration. This diagram gives the time-evolution of the heat release rate Q’ (h-1) related to the total heat Qtot (J) measured at the end of the calorimetry tests. There are samples with replacement percentage of 75% with FRAC (FRAC 75%) as well as with 50% (FRAC 50%) and 25% (FRAC 25%) respectively. The higher the substitution level is, the earlier the peak of heat rate is.

According to the previous calorimetry tests, FRCA affect obviously the cement hydration. The acceleration of cement hydration is normally answered by the increase of surface available for the nucleation of C-S–H, which correlated with the higher specific area FRAC in contrast to cement. But some scientists support that this theory about only the surface availability is not capable to explain this acceleration of hydration. The addition of finer parts decreases the interparticle distance, leading to an increase to the shear between the particles especially during mixing and therefore it raises the dissolved ions into the solution. Moreover, adding the nature and mineralogical structure of limestone enhances systematically the nucleation effect. It is obvious that the calcite chooses this effect in contrast aragonite. Also, FRCA may include anhydrous cement which could contribute to the heat release (Mahieux, 2020)

The substitution of cement by FRCA does not affect only the acceleration of the hydration but it also increases the degree of hydration of cement. Degrees of hydration are calculated as the ratio of the heat released by cement and the maximum heat for a complete hydration. The increase in hydration degree can be an outcome of the presence of FRCA but also from the increase of w/c ratio dependent on the replacement. Some results indicate that the effect of FRCA on cement hydration is similar with the observed for limestone filler. Regarding the compressive strengths, the higher the replacement rate, the lower relative compressive strength of mortars is. However, for a given specific substitution level, the relative compressive strengths are higher at age of 2 and 7 days than at 28 or 90 days. This is a result of the influence of the effect of acceleration and the increase of the hydraulic reactivity of cement with FRCA presence (Mahieux, 2020).

Chapter 3

Experimental study

Chapter 3 includes the total concept of the experimental study. It describes the general scheme of the experiments, the experimental phases and the method that was used for answering the first research question. Also, this chapter depicts the materials that used in the lab during the preparation of the experiments and the machinery with the general experimental procedure. There is a presentation of scientific methods in order to approach the investigation of the workability of the new mortars as well as their flexural and compressive strengths included many methods and formulas. Finally, there is a clear analysis about preparation, mixtures and measurements of three experiments.

3.1 The general concept of the experimental study

The experimental study of this research aims to evaluate the property of recycled ultrafine particles (RUP) that produced with HAS by studying their influence in cement pastes. Cement pastes composed of a commercial cement blended with different quantities of ultrafine recycled concrete particles from the HAS are prepared. It includes three different phases. At the first phase, HAS recycled ultrafine particles below 125 microns are employed at replacement rates of 5%, 10%, and 15% by weight of cement. At the second phase, the particle size of HAS ultrafines are reduced below 45 microns and similar substitution rate will be used in the mortar. At the third phase, recycled sand is used instead of natural sand to make the mortars, in order to check the effect of the combination of recycled sand with recycled concrete particles. In all phases of experiments, the following experimental procedures are performed. All results are compared with the reference samples for any added value.

In the Table 3.1 below, there is a presentation of a general scheme of the whole experimental study. This table depicts the three different experimental phases and the materials that used for the mixtures of the new mortars. Each column of this table corresponds to each phase of the experiment study.

EXPERIMENTAL STUDY		
1ST PHASE	2ND PHASE	3RD PHASE
natural sand water cement-5,10,15 % substitution with RUP	natural sand water cement-5,10,15 % substitution with RUP	recycled sand water cement-5,10,15 % substitution with RUP
RUP < 0,125mm	RUP < 0,045mm	RUP < 0,125mm

Table 3.1 The general scheme of the experimental study

3.2 The materials of the experimental study

The experimental study took place in the concrete lab of TU DELFT between February 2020 and April 2020. Different materials were used in the concrete lab for the mixing section. These materials were water, cement, natural sand, recycled sand and recycled ultrafine particles (RUP).

Water: Drinking water from the concrete lab was used for making the mortars and conducting the tests.

Cement: The cement that is used for mortar and concrete manufacture should be able to be kept for more than 24 h between sampling and testing, it shall be stored in completely filled and airtight containers made from a material which does not react with it. For the purposes of this research, Portland cement 52,5 R was used for the casting of the mortars in the concrete lab.

Natural sand: For mortars manufacture, natural sand from the concrete lab with specific size distribution was used in the mixtures. This natural sand had the following specific cumulative percentage of size distribution (Figure 3.1). The natural sand was used only in the 1st and 2nd phase of the experimental study. The size distribution of natural sand particles is also analysed in detail in the Table A of the Appendices.

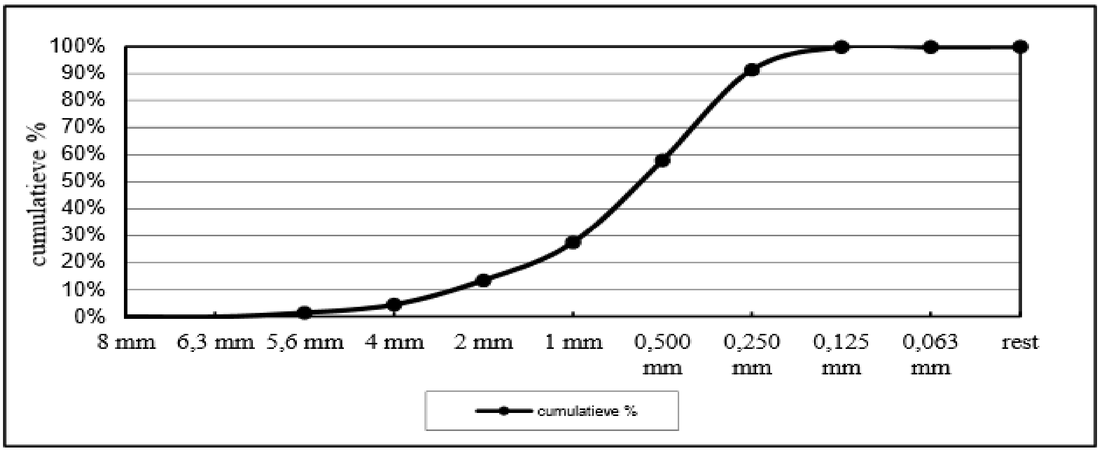

Figure 3.1 The cumulative percentage of size distribution of natural sand (DELFT_Concrete_Lab, 2020)

Recycled sand: The recycled sand was produced after the usage of HAS system and the separation between fine and ultrafine particles. It was used only in the 3rd phase of the experiment as a total replacement of natural sand. For the accuracy of the experiment, it should have the similar size distribution with the natural sand that was used in the first two phases of the experimental study. Hence, the method of sieving of the total recycled sand was used to fulfill the expectation of the same size distribution. The sieving method of the recycled sand will be explained in a next paragraph. This recycled sand had the following cumulative percentage of size distribution (Figure 3.2). The size distribution of recycled sand particles is also analysed in detail in the Table B of the Appendices.

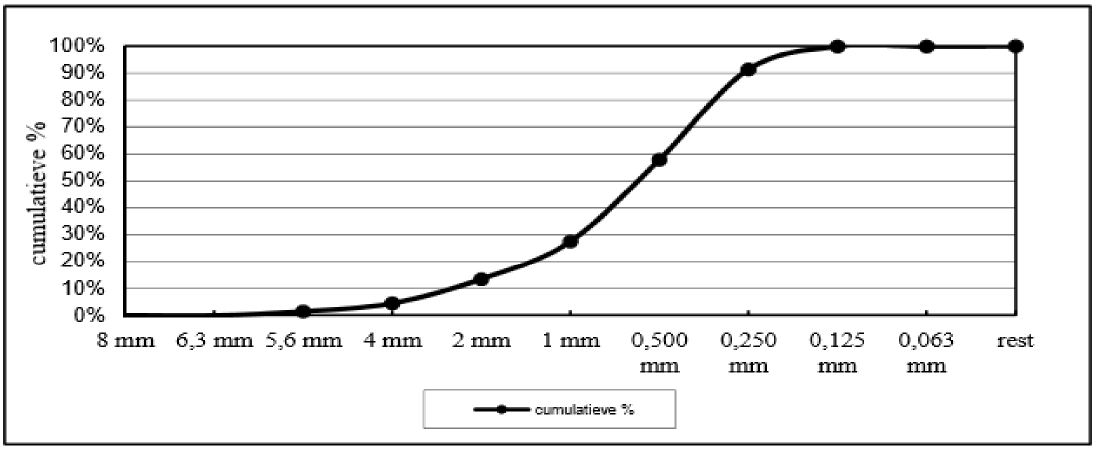

Figure 3.2 The cumulative percentage of size distribution of recycled sand

Recycled ultrafine particles (RUP): The recycled ultrafine particles were produced by HAS system. The outcome of HAS system has as a product, ultrafine particles below 125 microns. This size of RUP was used in the 1st and 3rd phase of the experiment as a substitution of cement in 5,10 and 15% respectively. In the 2nd phase of the experiment, the aim was to test how the size of the ultrafine particles could affect the properties of the mortars. Hence, the target was to substitute this time cement with recycled ultrafine particles below 45 microns. The methods of milling and sieving were used to convert the 125 microns RUP to 45 microns. The milling and sieving methods will be explained in a next paragraph.

3.3 The machinery and the general procedure of the experiments

For the three experiments that were conducted in the TU DELFT lab, there is a general procedure and specific machines that were used for the mixing, casting, saving and the strength measurement of the samples according to the Dutch norms.

For the mixing of the samples a small mixer was used, which was consisted of a stainless-steel bowl with a capacity of about 5L of the typical shape and size and a stainless-steel blade of the typical shape, size and tolerances. Blades and bowls should form sets which shall always be used together. In the beginning of the mixing, the water and cement should be weighted, and they were placed together in the bowl to get in contact in low speed. Next step was the addition of the sand and the recycled materials; if they were existed, depended on each case and mixing at high speed (NEN-EN-196-1, 2016). In the Figure 3.3 below, it is depicted the mixing machine and the bowl that was used during the experiments in the concrete lab.

Figure 3.3 The mixing machine and the bowl in the concrete lab of TU DELFT

After that, the appropriate molding of test specimens was very important. The test specimens were 40 mm × 40 mm × 160 mm prisms from polyethylene. In the Figure

3.4 below, the prisms are depicted. After the mixing and the preparation of the mortars, the moulding/casting of the samples was necessary. But before the moulding of the mortars, the slump test was obligatory in order to test consistency of the mortars. For the preparation of the slump test, the disc was wiped and the inner surface and edges of the mold was clean with a damp cloth. The mold was placed centrally on the disc of the flow table the mortar was put in two layers; each layer being compacted by at least 10 short strokes of the tamper to ensure uniform filling of the mold. The excess mortar was skimmed off with a palette knife and the free area of disc was kept clean and dry. Any water should be removed from around the bottom edge of the mold. After about 15 s, the mold was raised vertically, and the mortar run on the disc by jolting the flow table 15 times at a constant frequency of approximately one per second. The diameter of the mortar was measured in two directions at right angles to one another using calipers. The results were stated in mm to the nearest mm (Normalisatie-instituut, 2019).

Figure 3.4 The 40 mm × 40 mm × 160 mm prisms from polyethylene in the concrete lab of TU DELFT

In the Figure 3.5 below, there is a typical slump test tool for mortars.

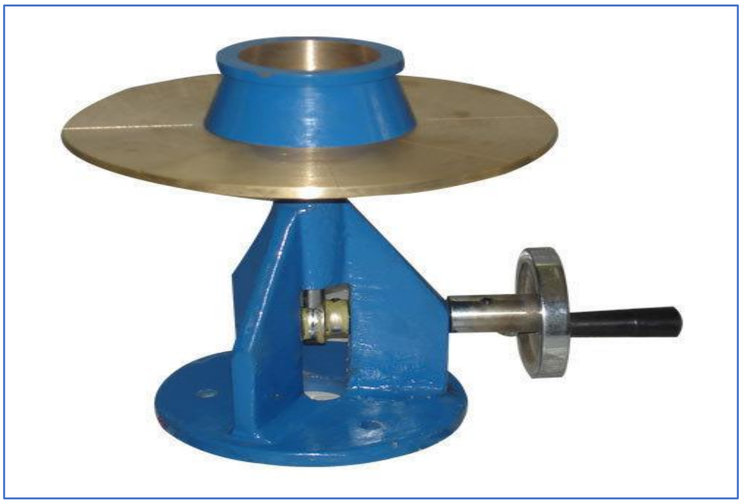

Figure 3.5 A typical slump test tool for mortars (© Accro-tech Scientific Industries., 2019)

Moreover, the mortars are initially placed onto the jolting table in order to remove the unnecessary air from inside the pores and the bonds. The jolting apparatus was consisted of a rectangular table connected firmly by two light arms to a pivot at nominally 800 mm from the centre of the table. The table shall incorporate at the centre of its lower face a projecting lug with a rounded face. Beneath the projecting lug should be a small stop with a plane upper surface. In the rest position, the common normal through the point of contact of the lug and the stop should be vertical. After 50-60 jolts, the moulds were lifted from the jolting table and the hopper was removed. Finally, the moulds were labelled for identification purposes (NEN-EN-196-1, 2016).

The samples with the fresh mortars in the jolting table are in the Figure 3.6 below:

Figure 3.6 The fresh mortars in the jolting table in the concrete lab of TU DELFT

The next step was the storage before demoulding. The moulds were covered with impermeable material which did not react with cement of approximate size 210 mm × 185 mm × 6 mm on the mould. The covered moulds were placed on a horizontal base in the moist air room until their right time for demoulding after one day. The demoulding of the specimen was significant procedure because it is important not to damage the samples. Carry out demoulding, for tests at ages should not be greater than 24 h, between 20 h and 24 h after moulding (NEN-EN-196-1, 2016).

The final part of the experimental study was the testing of the strengths of the samples. The suggested test ages were: 24 h ± 15 min, 48 h ± 30 min; 72 h ± 45 min, 7 d ± 2 h and 28 d ± 8 h (NEN-EN-196-1, 2016). For the purpose of this research, flexural and compressive strengths were only calculated but in different ages due to coronavirus issues. In the Figure 3.7 below, the machine, which was used for the measurements of flexural and compressive strengths is depicted.

Figure 3.7 The strength measurement machine in the concrete lab of TU DELFT

For the calculation of the flexural strength, the apparatus for the determination of flexural strength should be capable of applying loads up to 10 kN with an accuracy of ± 1,0 % of the recorded load in the upper four-fifths of the range being used, at a rate of loading of (50 ± 10) N/s. A three-point loading method with similar type of apparatus was used. The load was applied vertically by means of the loading roller to the opposite side face of the prism and it was increased for the measurement at the rate of (50 ± 10) N/s until fracture (NEN-EN-196-1, 2016). The prism halves were kept covered with a damp cloth until tested the compressive strengths. The flexural strength was measured automatically by the machine, but generally it is calculated by the formula (1) as it described in the following Dutch norm (NEN-EN-196-1, 2016) :

$$R_f = \frac{1{,}5 * F_f * l}{b^3} \quad (1)$$

where:

R_f is the flexural strength, in megapascals;

b is the side of the square section of the prism, in millimetres;

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

l is the distance between the supports, in millimetres.

For the estimation of the results, the flexural strength test result was calculated as the arithmetic mean of the three individual results, each expressed at least to the nearest 0,1 MPa, obtained from a determination made on a set of three prisms. The arithmetic mean is expressed to the nearest 0,1 MPa (NEN-EN-196-1, 2016).

Regarding the compressive strengths, the tests took place with the two halves moulds from the measurement of flexural strength. The testing machine for the determination of compressive strength should be of suitable capacity with accuracy of ± 1,0 % of the recorded load in the upper four-fifths of the range being used when verified in accordance with EN ISO 7500-1. It should provide a rate of load enhancement of (2400 ± 200) N/s. Each prism half was tested by loading its side faces using an equipment like this above. The load is increased at the rate of (2400 ± 200) N/s over the entire load application until fracture (NEN-EN-196-1, 2016).

The compressive strength was measured automatically by the machine, but generally it is calculated by the formula (2) as it is described in the following Dutch norm (NEN-EN-196-1, 2016).

$$R_c = \frac{F_c}{1600} \quad (2)$$

where:

Rc is the compressive strength, in megapascals;

Fc is the maximum load at fracture, in newtons;

1600 is the area of the platens or auxiliary plates (40 mm × 40 mm), in square millimetres.

For the estimation of the results, the compressive strength test result was calculated as the arithmetic mean of the six individual results, each expressed at least to the nearest 0,1 MPa, obtained from the six determinations made on a set of three prisms. When one result within the six individual results varied by more than ± 10 % from the mean, this result was discarded, and the arithmetic mean was calculated by the five remaining results. When one result within the five remaining results is varied by more than ± 10 % from their mean, the set of results was discarded and the determination was repeated (NEN-EN-196-1, 2016).

In the next paragraphs, there is a detailed analysis about the way that the 1^{st},2^{nd} and 3^{rd} experiments were conducted in the lab.

3.4 The preparation of the 1st experiment

The 1st experiment took place in the concrete lab of TU DELFT in February of 2020. The basic concept of this experiment was to assess the impact of using recycled ultrafine as cement replacement in a new mortar mix. This evidence could contribute to the technical feasibility of this new mortar.

CEM I was the reference mortar and was used to determine the effect of the ultrafine recycled concrete particles. At this first experimental phase, HAS recycled ultrafine particles were employed at replacement rates of 5%, 10%, and 15% by weight of cement in the new mortars. After that, there was a contrast between the new mortars and CEM I regarding their flexural and compressive strengths. The materials for this experiment consisted of a Portland cement 52,5 R, natural sand 0-4mm, distilled water and recycled ultrafine particles below 125 microns. All the materials were provided by the concrete lab of TU DELFT.

In the following Table 3.2, there is the composition of the mortar mixtures of the 1st experiment:

Mortar Pastes	Cement I (g)	Sand (g)	Water (g)	Recycled ultrafine (g) <0,125mm	w/b ratio	w/c ratio	Number of samples
CEMI - Ref.	200	600	100	0	0,5	0,5	12
CEMI – 5% RUP	190	600	100	10	0,5	0,53	12
CEMI - 10% RUP	180	600	100	20	0,5	0,56	12
CEMI - 15% RUP	170	600	100	30	0,5	0,59	12

Table 3.2 The recipe of the mortar mixture of 1st experiment

For the preparation of the 1st experiment, there was a need for four different mixtures that would help for the results and the conclusion. According to the guidelines from the paragraph 3.3 regarding the flexural and compressive, it was necessary for the measurement of flexural strengths to have 3 samples, that would be split after the measurements and would become 6 for the measurement of the compressive strengths. The target was the measurements of flexural and compressive strengths to be done in four different ages 1,7,14 and 28 days respectively. Hence, four different days with combination of 3 samples for the flexural strengths led to the necessity of 12 samples for each mixture of the 1st experiments. So, 48 samples in total included in the 1st experiment.

The first mixture in the 1st experiment was the reference one with only cement without any replacement with RUP below 125 microns. It was named as CEMI – Reference. The target is the preparation of 12 mortars with the same composition and enough quantities of materials for the accomplishment of the slump test and the molding for flexural and compressive strengths. The quantity for cement was 200g for one mortar, leading to total weight of 2,4 kg for the total 12 samples. The ratio of cement with sand was 1:3, so sand was 600 g for each sample and 7,2kg in total for all the mortars. There were no recycled ultrafine particles as replacement, so 0 kg. The w/b should be always constant during the experiment 0,5. Hence, the water quantity was 1,2kg and the w/c ratio was 0,5 (1,2 kg water/2,4 kg cement). The second mixture in the 1st experiment was the one with 5% of substitution of cement with recycled RUP below 125 microns. It was labelled as CEMI - 5% RUP. The quantity for cement this time was 10g less than the first mixture. So, 190 g for one sample and totally 2,28 kg for 12 samples. This 10g is replaced with RUP in this mixture, which is now 5% of initial cement quantity in the reference sample, so 120g for all this mixture. Hence, the total binder quantity was again 2,4 kg (2,28 kg cement + 0,12kg RUP). The ratio of binder with sand was 1:3, so sand was 600g for one sample and 7,2kg in total. The w/b should be always constant during the experiments 0,5. Hence, the water quantity was 1,2kg but the w/c ratio was 0,53 (1,2 kg water/2,28 kg cement). The third mixture in the 1st experiment was the one with 10% of substitution of cement with RUP below 125 microns. It was named as CEMI - 10% RUP. The quantity for cement this time was 180g this time for each mortar and 2,16 kg for 12 samples. At this mixture, RUP were 10% of cement quantity in the reference sample, so 20g for this mortar and 240g in total mixture. Hence, the total binder quantity was again 2,4 kg (2,16 kg cement +0,24kg RUP). The ratio of binder with sand was 1:3, so sand was 600g for one sample and 7,2kg in total. The w/b should be always constant during the experiments 0,5. Hence, the water quantity was 1,2kg but the w/c ratio was this time 0,56 (1,2 kg water/2,16 kg cement). The fourth mixture in the 1st experiment was the one with 15% of substitution of cement with RUP below 125 microns. It was labelled as CEMI - 15% RUP. The quantity for cement this time was 170 g for each sample and 2,04 kg in total. The RUP were 15% of cement quantity in the reference sample, so 30g in each sample and 360g in the fourth mixture of this experiment.. Hence, the total binder quantity was again 2,4 kg (2,04 kg cement +0,36kg RUP). The ratio of binder with sand was 1:3, so sand was again 600g and 7,2kg for all the mortars. The w/b should be always constant during the experiments 0,5. Hence, the water quantity was 1,2kg but the w/c ratio was 0,59 (1,2 kg water/2,04 kg cement).

3.5 The preparation of the 2nd experiment

The 2nd experiment took place in the concrete lab of TU DELFT in February of 2020. The basic concept of this experiment was to evaluate the particle size of the recycled ultrafine material can affect the strength of new mortars. This evidence could contribute to the final technical feasibility of this new mortar.

CEM I from the 1st experiment was the reference mortar and was used to determine the effect of the ultrafine recycled concrete particles (paragraph 3.4). At this second experimental phase, HAS recycled ultrafine particles below 45 microns were employed at replacement rates of 5%, 10%, and 15% by weight of cement in the new mortars. In order to convert recycled ultrafine particles from 125 to 45 microns, the procedures of milling and sieving took place before the mixing of the mortars. After that, there was a contrast between the new mortars and CEM I regarding their flexural and compressive strengths. The materials for this experiment consisted of a Portland cement 52,5 R, natural sand 0-4mm, distilled water and recycled ultrafine particles below 45 microns. All the materials were provided by the concrete lab of TU DELFT.

In the following Table 3.3, there is the composition of the mortar mixtures of the 2nd experiment:

Mortar Pastes	Cement I (g)	Sand (g)	Water (g)	Recycled ultrafine (g) <0,045mm	w/b ratio	w/c ratio	Number of samples
CEMI - Ref.	200	600	100	0	0,5	0,5	12
CEMI - 5% RUP	190	600	100	10	0,5	0,53	12
CEMI - 10% RUP	180	600	100	20	0,5	0,56	12
CEMI - 15% RUP	170	600	100	30	0,5	0,59	12

Table 3.3 The recipe of the mortar mixture of 2nd experiment

For the preparation of the 2nd experiment, there was a need for three different mixtures in addition to CEM I (reference sample) from the first experiment that would help for the result and conclusion. The measurements from the samples of these 3 new mixtures would be in contrast with the measurements of the reference sample. According to the guidelines from the paragraph 3.3 regarding the flexural and compressive, it was necessary for the measurement of flexural strengths to have 3 samples, that would be split after the measurements and would become 6 for the measurement of the compressive strengths. The target was the measurements of flexural and compressive strengths to be done in four different ages 1,7,14 and 28 days respectively. Hence, four different days with combination of 3 samples for the flexural strengths led to the necessity of 12 samples for each mixture of the 2nd experiment. So, 36 samples in total included in the 2nd experiment. The difference in contradiction to the 1st experiment is that the recycled ultrafine particles that were used, were below 45 microns. The goal of this experiment is to reveal the effect of the size particle.

The conversion of recycled particles from 125 to 45 microns was done with the procedures of milling and sieving, as they are described below:

- <u>Milling:</u> A mill is a device that breaks solid materials into smaller pieces by grinding, crushing and or cutting. The procedure of milling is a significant operation in many concrete processes (Thomas & Filippov, 1999). Also, there are many different types of mills and many types of materials processed in them. The machine that was used, was powered by electricity. The target here of milling was to size the recycled ultrafine material. Quantity of recycled ultrafine particles was placed in many terms in the machine in the Figure 3.8 below. Each milling procedure lasted about 1 minute in this rotation machine at medium speed. The recycled ultrafine particles were very hot after milling machine. After that the sample were placed for the sieving procedure (Thomas & Filippov, 1999).

Figure 3.8 The milling machine during 2nd experiment in the concrete lab of TU DELFT

- Sieving: The next step after milling procedure was sieving. The target of the sieving was to separate the recycled particles below 45 microns with the bigger ones. For this procedure a sieving machine was used with 0,045 mm sieve. It is depicted in the Figure 3.9. The recycled particles were places for 5 minutes in this shaking machine. The particles that went through the sieve in the side below, were the right ones below 45 microns. Hence, the smaller particles than 0,045 mm could be used for the 2nd experiment.

Figure 3.9 The sieving machine during 2nd experiment in the concrete lab of TU DELFT

The target was the assessment of impact of RUP particle size. Hence, it was useful the preparation of 12 mortars with the same composition and enough quantities of materials for the accomplishment of the slump test and the molding for flexural and compressive strengths. The first mixture in the 2nd experiment was the reference one with only cement without any replacement with RUP below 45 microns. It was named as CEMI – Reference. The quantity for cement was 200g for one mortar, leading to total weight of 2,4 kg for the total 12 samples. The ratio of cement with sand was 1:3, so sand was 600 g for each sample and 7,2kg in total for all the mortars. There were no recycled ultrafine particles as substitution material, so 0 kg. The w/b should be always constant during the experiments 0,5. Hence, the water quantity was 1,2kg and the w/c ratio was 0,5 (1,2 kg water/2,4 kg cement). The second mixture in the 2nd experiment was the one with 5% of substitution of cement with recycled RUP below 45 microns. It was labelled as CEMI - 5% RUP. The quantity for cement this time was 10g less than the first mixture. So, 190 g for one sample and totally 2,28 kg for 12 samples. This 10g is replaced with RUP in this mixture, which is now 5% of initial cement quantity in the reference sample, so 120g for all the 2nd experiment. Hence, the total binder quantity was again 2,4 kg (2,28 kg cement +0,12kg RUP). The ratio of binder with sand was 1:3, so sand was 600g for one sample and 7,2kg in total. The w/b should be always constant during the experiments 0,5. Hence, the water quantity was 1,2kg but the w/c ratio was 0,53 (1,2 kg water/2,28 kg cement). The third mixture in the 2nd experiment was the one with 10% of substitution of cement with RUP below 45 microns. It was named as CEMI - 10% RUP. The quantity for cement this time was 180g this time for each mortar and 2,16 kg for 12 samples. At this mixture, RUP were 10% of cement quantity in the reference sample, so 20g for this mortar and 240g in total mixture. Hence, the total binder quantity was again 2,4 kg (2,16 kg cement +0,24kg RUP). The ratio of binder with sand was 1:3, so sand was 600g for one sample and 7,2kg in total. The w/b should be always constant during the experiments 0,5. Hence, the water quantity was 1,2kg but the w/c ratio was this time 0,56 (1,2 kg water/2,16 kg cement). The fourth mixture in the 2nd experiment was the one with 15% of substitution of cement with RUP below 45 microns. It was labelled as CEMI - 15% RUP. The quantity for cement this time was 170 g for each sample and 2,04 kg in total. The RUP were 15% of cement quantity in the reference sample, so 30 g in each sample and 360 g in the whole fourth mixture. Hence, the total binder quantity was again 2,4 kg (2,04 kg cement +0,36kg RUP). The ratio of binder with sand was 1:3, so sand was again 600g and 7,2kg for all the mortars. The w/b should be always constant during the experiments 0,5. Hence, the water quantity was 1,2kg but the w/c ratio was 0,59 (1,2 kg water/2,04 kg cement).

3.6 The preparation of the 3rd experiment

The 3rd experiment took place in the concrete lab of TU DELFT in March of 2020. The basic concept of this experiment was to evaluate the formulation of a new mortar recipe that incorporates recycled sand and recycled ultrafine particles. This evidence could contribute to the technical feasibility of this new mortar.

CEM I-REF from the 1st experiment was the reference mortar and was used to determine the effect of the ultrafine recycled concrete particles. In contrast to the previous two experiments, the natural sand is substituted totally with recycled sand with the same size distribution. So, there was a mixture without recycled ultrafine particles substitution, but with recycled sand substitution which was called CEM I-RS. At this third experimental phase, HAS recycled ultrafine particles were employed at replacement rates of 5%, 10%, and 15% by weight of cement in these new mortars with recycled sand replacing natural sand. After that, there was a contrast between the new mortars and CEMI-REF regarding their flexural and compressive strengths. The materials for this experiment consisted of a Portland cement 52,5 R, recycled sand 0-4mm, distilled water and recycled ultrafine particles below 125 microns. All the materials were provided by the concrete lab of TU DELFT.

In the following Table 3.4, there is the composition of the mortar mixtures of the 3rd experiment:

Mortar Pastes	Cement I (g)	Natural Sand (NS) / Recycled Sand (RS) (g)	Water (g)	Recycled ultrafine (g) <0,125mm	w/b ratio	w/c ratio	Number of samples
CEMI - Ref.(exp1)	200	600 (NS)	100	0	0,5	0,5	12
CEMI - RS	200	600 (RS)	133,3 (100+33,3)	0	0,67	0,67	12
CEMI - 5% RUP - RS	190	600 (RS)	133,3 (100+33,3)	10	0,67	0,7	12
CEMI - 10% RUP-RS	180	600 (RS)	133,3 (100+33,3)	20	0,67	0,74	12
CEMI - 15% RUP-RS	170	600 (RS)	133,3 (100+33,3)	30	0,67	0,78	12

Table 3.4 The recipe of the mortar mixture of 3rd experiment

For the preparation of the 3rd experiment, there was a need for four different mixtures in addition to CEM I (reference sample) from the first experiment that would help for the result and conclusion. The measurements from the samples of these 4 new mixtures would be in contrast with the measurements of the reference sample. According to the guidelines from the paragraph 3.3 regarding the flexural and compressive, it was necessary for the measurement of flexural strengths to have 3 samples, that would be split after the measurements and would become 6 for the measurement of the compressive strengths. The target was the measurements of flexural and compressive strengths to be done in four different ages 1,7,14 and 28 days respectively. Hence, four different days with combination of 4 samples for the flexural strengths led to the necessity of 12 samples for each mixture of the 3rd experiment. So, 48 samples in total included in the 3rd experiment. The important difference in contradiction to the other two experiments was the use of the recycled sand. As it was referred in the literature review, recycled sand has bigger water absorptivity than the natural sand. Hence, in the training samples before the experiment with same addition of water of 100g for each sample and 1200g (100*12) in total for each mixture, the final mortars were so dry with no flexural and compressive strengths. So, it was obligatory the compensation of extra 33,3 g of water for each sample and 400 g (33,3*12) water in total for each mixture. Hence, each mixture of the 4 during the 3rd experiment included 1600g (1200+400) of water in total, in order to help samples to increase strengths and humidity. This led to an increase of w/b ratio and w/c ratio of the mortars due to bigger quantity of water, something that would affect the measurements in tests of mortars.

Also, before the mixing procedure it was significant to convert the recycled sand in the same size distribution 0-4 mm with natural sand. For this process, it was necessary the usage of a big sieving machine for concrete. This recycled sand should have the appropriate specific size distribution as it was described in the Figure 3.2. For this purpose, multiple sieves were used in the sieving machine. The diameter of the sieves was 5.6, 4, 2, 1, 0.5, 0.25 and 0.125mm. Figure 3.10 shows the sieving machine used in this study. The quantity of the recycled sand was placed in terms in the cyclic surface of the bigger sieve and after 5 minutes of shaking with sieving machine, the recycled particles were collected from each sieve along to their size. This process took place until to have the appropriate quantities for all the sizes according to the suggested recycled sand size. The goal was the same size distribution of recycled particles as the ones from natural sand. This procedure of sieving the recycled sand, it was followed by the mixing process.

Figure 3.10 The sieving machine during 3rd experiment in the concrete lab of TU DELFT

The goal was in this experiment the assessment of impact of recycled sand with or without RUP. Hence, it was helpful the preparation of 12 mortars with the same composition and enough quantities of materials for the accomplishment of the slump test and the molding for flexural and compressive strengths. The first mixture in the 3rd experiment was the one with only cement and recycled sand without any replacement with RUP below 125 microns. It was named as CEMI – RS. The quantity for cement was 200g for one mortar, leading to total weight of 2,4 kg for the total 12 samples. The proportion of cement with sand was 1:3, so sand was 600 g for each sample and 7,2kg in total for all the mortars. There were no recycled ultrafine particles as substitution material, so 0 kg. The w/b was always constant during the 3rd experiment 0,67 but increased in contrast to the 0,5 of the first two experiments due to the addition of extra water during mixing. Hence, the water quantity was 1,6 kg and the w/c ratio was 0,67 (1,6 kg water/2,4 kg cement). The second mixture in the 3rd experiment was the one with 5% of substitution of cement with recycled RUP below 125 microns. Also, it had 100% substitution of natural sand with recycled sand. It was labelled as CEMI - 5% RUP-RS. The quantity for cement this time was 10g less than the first mixture. So, 190 g for one sample and totally 2,28 kg for 12 samples. This 10g is replaced with RUP in this mixture, which is now 5% of initial cement quantity in the reference sample, so 120g for all this mixture. Hence, the total binder quantity was again 2,4 kg (2,28 kg cement +0,12kg RUP). The ratio of binder with sand was 1:3, so sand was 600g for one sample and 7,2kg in total. The w/b was always constant during the experiments 0,67 but increased in contrast to the 0,5 of the first two experiments due to the addition of extra water as it referred before. Hence, the water quantity was 1,6 kg but the w/c ratio was 0,7 (1,6 kg water/2,28 kg cement). The third mixture in the 3rd experiment was the one with 10% of substitution of cement with RUP below 125 microns. Also, it had 100% substitution of natural sand with recycled sand. It was named as CEMI - 10% RUP-RS. The quantity for cement this time was 180g this time for each mortar and 2,16 kg for 12 samples. At this mixture, RUP were 10% of cement quantity in the reference sample, so 20g for this mortar and 240g for the whole mixture. Hence, the total binder quantity was again 2,4 kg (2,16 kg cement +0,24kg RUP). The ratio of binder with sand was 1:3, so sand was 600g for one sample and 7,2kg in total. The w/b was always constant during the experiments 0,67 but increased in contrast to the 0,5 of the first two experiments due to the addition of extra water as it referred before. Hence, the water quantity was 1,6 kg but the w/c ratio was 0,74 (1,6 kg water/2,16 kg cement). The fourth mixture in the 3rd experiment was the one with 15% of substitution of cement with RUP below 125 microns. Also, it had 100% substitution of natural sand with recycled sand. It was labelled as CEMI - 15% RUP-RS. The quantity for cement this time was 170 g for each sample and 2,04 kg in total. The RUP were 15% of cement quantity in the reference sample, so 30g in each sample and 360 g in total for the fourth mixture. Hence, the total binder quantity was again 2,4 kg (2,04 kg cement +0,36kg RUP). The ratio of binder with sand was 1:3, so sand was again 600g and 7,2kg for all the mortars. The w/b was always constant during the experiments 0,67 but increased in contrast to the 0,5 of the first two experiments due to the addition of extra water as it referred before. Hence, the water quantity was 1,6 kg but the w/c ratio was 0,78 (1,6 kg water/2,04 kg cement).

Chapter 4

Results and discussion

Chapter 4 includes the discussion of results based on the experimental study. It describes the results of the slump tests and the flexural and compressive strength tests of the three experiments and their interpretation. It also comprises the findings of the study in general. It reveals the impact of recycled ultrafine particles, the impact of RUP particle size and the consequences of the usage of recycled sand instead of natural sand. There is also a comparison between the results of the experiments. All the results and discussion in this chapter can give answer to the first research question of this MSc thesis.

4.1 Impact of recycled ultrafine particles (RUP)

The impact of recycled ultrafine particles (RUP) in the concrete/mortar production is provided by results of the 1st experiment. In the section 4.1.1, the workability of fresh mortar with this recycled ultrafine powder is investigated through the results from the slump test. In the section 4.1.2, there is the analysis of the flexural strength test and in section 4.1.3 that from the compressive strength test. The target of the 1st experiment is the assessment of the impact of using recycled ultrafine as cement replacement in a new mortar mix.

4.1.1 Workability of fresh mortar

The first test for the mortars after the mixing procedure was the slump test as it as referred in the paragraph 3.3. The mixture from the 1st experiment was placed in the appropriate machine. For the 1st experiment, the results of the slump test with size 100x70x60mm are depicted in the Table 4.1 below in details:

slump test				
	measurement diameters (cm)		mean (cm)	deviation 1st/2nd %
CEM 1	17,8	18	17,9	0,56/0,56
CEM 1-5%RUP	18	17.8	17,9	0,56/0,56
CEM1-10%RUP	20.8	21	20,9	0,48/0,48
CEM1-15%RUP	20.2	20.4	20,3	0,49/0,49

Table 4.1. Results of slump test of the 1st experiment

According to the Table 4.1, the results from the slump test of the 1st experiment seem to be valuable. The norms suggest that in the slump test of the mortars, the mean value is defined as the flow value for the test sample. If the individual flow values from the two test samples deviate from their mean value by less than 10 %, this means that this mean value can be used as the flow value of the mortar. If the two individual flow values deviate from their mean value by more than 10 %, the slump test should be repeated using further mortar from the reduced bulk test sample. Finally, if the results deviate from the mean value by less than 10%, then the mean value from the repeat test can be used as the flow value of the mortar. But supposing that the results differ by more than 10%, the measurements are considered as non-valid and the mixing procedure should be done again. Here the deviation for all the four mixtures are less than 10%. The deviation for the reference mixture CEM1 was 0,56%, for the mixture CEM 1-5% RUP was again 0,56%, for the mixture CEM1-10% RUP was 0,48% and for the mixture CEM1-15% RUP was 0,49%. Hence, the mean value of the measurements of the two angles can be used as flow values. This is a first step for the validity of the slump test results. The mean value for the reference mixture CEM1 was 17,9 cm, for the mixture CEM 1-5% RUP was again 17,9 cm, for the mixture CEM1-10% RUP was 20,9 cm and for the mixture CEM1-15% RUP was 20,3 cm.

Moreover, regarding the table 4.1, as the substitution rate of recycled ultrafine particles increases until 10%, the mean flow value is enhanced, so higher fresh-state workability. Also, the mortar with 15% of RUP replacement has a very good value of slump. Another important point is that as the substitution rate of RUP increased, the sample in the slump test in the conical mold was wetter, so the slump was more liquid. This situation can be also characterized as bleeding phenomenon. Bleeding is a phenomenon where water in a freshly mixed cement-based material is drained out to the surface when solid components of the mixture consolidate in a form. The bleeding influences the quality of fresh concrete and durability after the concrete hardened (Jae, Hong, & Kwak, 2014). The amount and rate of drained-out water are considered to be two important bleeding parameters, which are mainly determined by the dimensional properties of the concrete mix, environmental conditions where it stands, mix proportion and protocol, and characteristics of the constituents such as the size and shape of cement as well as aggregates (Jae et al., 2014). There are some ways to reduce bleeding (Claude Goguen, 2014):

- Reduce water content. Use lower slump mix;
- Use finer cements;
- Increase amount of fines in the sand;
- Use supplementary cementitious materials;
- Use air entraining admixtures.

As, it has already mentioned in chapter 3, in the 1st experiment there was an increase in the w/c ratio as the replacement ratio of the RUP also enhanced. Hence, this higher w/c ratio for the samples with replacement of RUP, also contributes for these positive results with the higher slumps and the better workability. It is obvious that the increased w/c ratio with the excess of water is a factor that probably can affect the results of the slump test of the samples with recycled ultrafine particles. Also, it should be considered that the packing density of the mortar tends to increase with the cement substitution with RUP. This may be explained by a better arrangement of the solid particles. This result is in good concordance with tendencies observed for slump. In fact, with an increasing packing density, the amount of water needed to fill the porosity decreases and more water is available to make the mortar fluid (Mahieux, 2020). This point can contribute to the higher values in the observations for the slumps with higher replacement ratio of RUP. The value of slumps seems enough and satisfactory for this experiment.

4.1.2 Mechanical properties -Flexural strength

After the demolding of the samples, the flexural strength of the mortars is examined in the lab at four different ages 1,7,14 and 28 days respectively. Due to covid-19 and the following cancellation of the last age of measurement of the 1st experiment, there are only measurements of flexural strength for the 1,7 and 14 day. This cannot give a final definite result regarding the flexural strength due to lack of enough data. Because at 28 days the mortar is expected gain most of its strength, thus, 28 days flexural strength is crucial. But it can give an important forecast and some useful conclusions about the effectiveness of recycled ultrafine particles. The Figure 4.1 below depicts with flows the mean values of the flexural strength of the 1st experiment. Also, the Table C in the Appendices shows in detail the average flexural strength for all the samples per day of measurement.

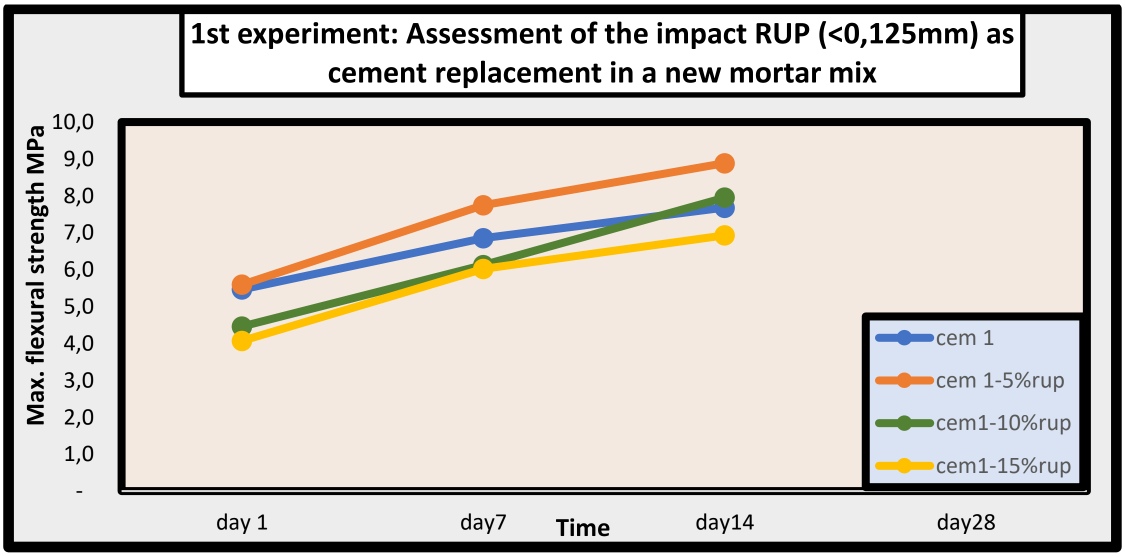

Figure 4.1 Diagram of the flexural strength test of the 1st experiment

According to the Figure 4.1, the CEM1 reference mortar samples have an average flexural strength of about 5,5 MPa in the day1, which it enhances during the other measurements of the next ages with 6,9 MPa in the day 7 and 7,7 MPa in the day14. The CEM1-5% RUP mortar samples have the higher average flexural strength in the whole 1st experiment with about 5,6 MPa in the day1, which it increases during the other measurements of the next ages with 7,8 MPa in the day 7 and 8,9 MPa in the day14. Also, the cem1-10% RUP mortar samples have higher average flexural strength than the reference ones in the day14 with 8,0 MPa. Results also seem to be sufficient regarding the CEM1-15% RUP mortar samples, they have an average flexural strength of about 4,1 MPa in the day1, which it increases during the other measurements of the next ages with 6 MPa in the day 7 and 6,9 MPa in the day14.

Hence, according to the previous figure, there are some important conclusions. At 14 days, mortars with 5 and 10 % replacement of RUP have bigger flexural strength than the reference sample without RUP. Moreover, at 14 days there is a peak in the diagram for mortar with 5% RUP with 8,9 MPa average flexural strength. The problem of the high porosity of RUP did not affect the concrete/mortar performance regarding flexural strengths negatively because a part of the mixing water that used for cement hydration was absorbed by the FRCA, it affected the dynamic mixing process, leading to the release of part of water into the paste affecting the w/c ratio (Evangelista & Brito, 2014). Mortar with 15 % RUP has only a slightly reduced average flexural strength in contrast to the reference one with 10% decrease (6,9/7,7 MPa) at 14 days. But the result is still satisfactory. The experiment indicates:

- The replacement with 5 and 10% of RUP can increase the performance of mortar regarding the flexural strength, leading to better resistance to deformation under bending (increase elasticity)
- The replacement with 15 % or over of RUP seems to decrease slightly the performance of mortar regarding the flexural strength due to lower compaction.

The higher w/c ratio during the measurement of the flexural strengths, which is increased as the replacement ratio also gets increased, maybe also improves the flexural strengths, because otherwise insufficient water could lead to lower results regarding the flexural strengths.

4.1.3 Mechanical properties - Compressive strength

After the demolding and the measurement of the flexural strengths of the samples, the following procedure was the measurement of the compressive strengths of the mortars with the 6 samples for each mixture. The compressive strength was about to be measured in four different ages 1,7,14 and 28 days respectively. Due to covid-19 and the following cancellation of the last age of measurement of the 1st experiment, there are only measurements of compressive strength for the age 1,7 and 14 day.

Although, that 28 days compressive strength is critical for the final conclusions, 14 days compressive strengths could give a valid result and a significant forecast about the usage of recycled ultrafine particles in concrete production. The Figure 4.2 below depicts with flows the mean values of the compressive strength of the 1st experiment. Also, the Table D in the Appendices shows in detail the average compressive strength for all the samples per day of measurement.

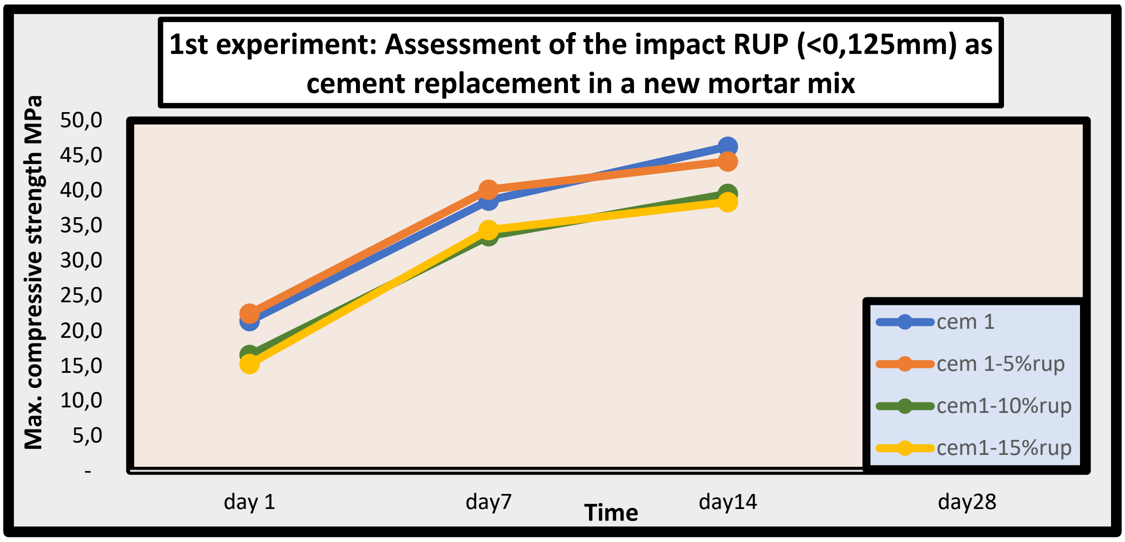

Figure 4.2 The diagram of the compressive strength test of the 1st experiment

Regarding the Figure 4.2, some useful observations could be revealed about the compressive strengths. The CEM1 reference mortar samples have an average compressive strength of about 21,4 MPa in the day1, which it inclines during the other measurements of the next days with 38,6 MPa in the day 7 and 46,3 MPa in the day14, which it was the highest. The CEM1-5%RUP mortar samples have high average compressive strength close to the reference sample with about 22,4 MPa in the day1, which shows great increase during the other measurements of the next ages with 40,1 MPa in the day 7 and 44,2 MPa in the day14. Moreover, the CEM1-10%RUP and the CEM1-15%RUP mortar samples have satisfactory average compressive strength in comparison to the reference samples. The first has about 16,5 MPa in the day1, which it enhances during the other measurements of the next days with 33,5 MPa in the day 7 and 39,5 MPa in the day14. Regarding the CEM1-15% RUP mortar samples, they have an average compressive strength of about 15,3 MPa in the day1, which it has an enough improvement in the next ages with 34,4 MPa in the day 7 and 38,4 MPa in the day14.

Furthermore, there are some significant points are revealed. Initially, at 14 days the reference mortar seems to have better compressive strength than the RUP containing mortars with its higher value. The reduction of the average compressive strengths in the 5%- RUP containing mortars is not important with 5%. But the reduction for 10%-15% RUP containing mortars seems to be notable with 15% and 17% respectively. RUP have some different features in contrast to cement particles and these characteristics can be possible reasons for this decrease according to the literature. Generally, the fine grade of the RCA has very high water absorption. This means that these recycled particles absorb more water than NA particles. Consequently, RUP below 125 microns have high water absorption (Zhao et al., 2015). Also, RUP below 125 microns as partial substitute of cement in a mortar/concrete mixture, can contribute to the hydraulic reactions. The specific area of RUP is higher than this of cement particles. This can lead to acceleration of cement hydration due to the increase of surface available for the nucleation of C-S-H (Mahieux, 2020). Furthermore, it is thought that the compressive strength of mortar/concrete can be affected by the substitution level of RUP; higher replacement ratios mean lower compressive strengths and by the quality as well as the origin of recycled aggregates (Evangelista & Brito, 2014).

Finally, at young ages of 1 and 7 days, mortar with 5% RUP has better performance than the reference one samples. As the time goes by, the average compressive strengths of all mortars have a great increase. Finally, a general observation about this diagram is that as the replacement ratio of recycled ultrafine gets increased, the average compressive strengths are slight decreased. In conclusion, the results are still satisfactory, with the average compressive strengths of the mortars with recycled ultrafine particles being high close to the reference one.

4.2 Impact of RUP particle size

The analysis of the 2nd experiment reveals the impact RUP particle size in the mortar/concrete production. It includes in the section 4.2.1 the results from the slump test and the assessment of the workability of the fresh mortar with the smaller recycled ultrafine particles. The next sections describe the mechanical properties of the new mortars. In the section 4.2.2, there is the analysis of the flexural strength test and in section 4.2.3 that from the compressive strength test. The goal of the 2nd experiment is the evaluation of particle size of the recycled ultrafine material on the strength of mortar. The difference in contrast to the 1st experiment, as it has already been referred, is that the recycled ultrafine particles has size below 0,045 mm instead of 0,125 mm.

4.2.1 Workability of fresh mortar

The first test for the mortars after the mixing procedure was the slump test as it as referred in the paragraph 3.3. For the 2nd experiment, the results of the slump test which lead to the evaluation of the workability of the new mortars with smaller RUP are depicted in the Table 4.2:

slump test				
	measurement diameters (cm)		mean (cm)	deviation 1st/2nd %
CEM 1	17,8	18	17,9	0,56/0,56
CEM 1-5%RUP	20,6	20	20,3	1,47/1,47
CEM1-10%RUP	22	21,6	21,8	0,91/0,91
CEM1-15%RUP	22	21,4	21,7	1,38/1,38

Table 4.2 Results of slump test of the 2nd experiment

Based on the above results, the deviation of the four mixtures are less than 10%. Hence, the mean value of the measurements of the two angles can be used as flow values. The mixtures CEM1-10%RUP and CEM1-15%RUP have the highest slump values with 21,8 cm and 21,7 cm respectively. The mixture CEM1-5%RUP has average slump value 20,3 cm and the reference sample has 17,9 cm.

As the substitution rate of RUP increases, the mean slump value is enhanced, so higher fresh-state workability. One possible explanation for this observation is that only the w/b ratio during experiments was kept constant, but not the w/c ratio. Due to the reduction of cement quantity and its replacement with RUP in the new mortars, there is excess of water in the mixtures and the w/c ratio of the mixtures is increased, as the substitution rate also is enhanced. Hence, this creation of excess of water can contribute to the higher slump values. Another important point is that the packing density tends to increase with the cement substitution with RUP. This may be explained by a better arrangement of the solid particles. This information can be combined with the previous observations for slump. Indeed, with an increasing packing density of mortar, the amount of water needed to fill the porosity decreases and more water is available to make the mortar fluid (Mahieux, 2020) . The results regarding the workability of fresh mortar in these experiments seem satisfactory. That means that the smaller size of RUP can improve the slump value or at least conclude to similar results.

4.2.2 Mechanical properties -Flexural strength

The flexural strength was measured in four different ages 1,7,14 and 28 days respectively. Due to covid-19 and the following cancellation of the last age of measurement of the 2nd experiment, there are only measurements of flexural strength for the 1,7 and 14 days. This could give some important results and a useful forecast about the effectiveness of milling recycled ultrafine particles even though that the last day (28 day) of flexural strength measurements (28 day) has the highest expected strengths. The diagram in Figure 4.3 below shows with flows the mean values of the flexural strength of the 2nd experiment. Also, the Table E in the Appendices analyses thoroughly the average flexural strength for all the samples per day of measurement.

In the diagram below, the CEM1-5%RUP mortar samples have the higher average flexural strength in the whole 2nd experiment with about 4,0 MPa in the day1, which it has great increase with 6,9 MPa in the day 7 and 8,2 MPa in the day14, which is the highest value during the 2nd experiment. Also, the CEM1-10%RUP mortar samples have high average flexural strength similar with the previous one, with about 4,1 MPa in the day1, which it increases with 6,7 MPa in the day 7 and 8,1 MPa in the day14. The results also for the CEM1-15%RUP mortar samples seem to be satisfactory. They have an average flexural strength of about 3,9 MPa in the day1, which it is increased during the other measurements of the next ages with 6,6 MPa in the day 7 and 7,8 MPa in the day14.

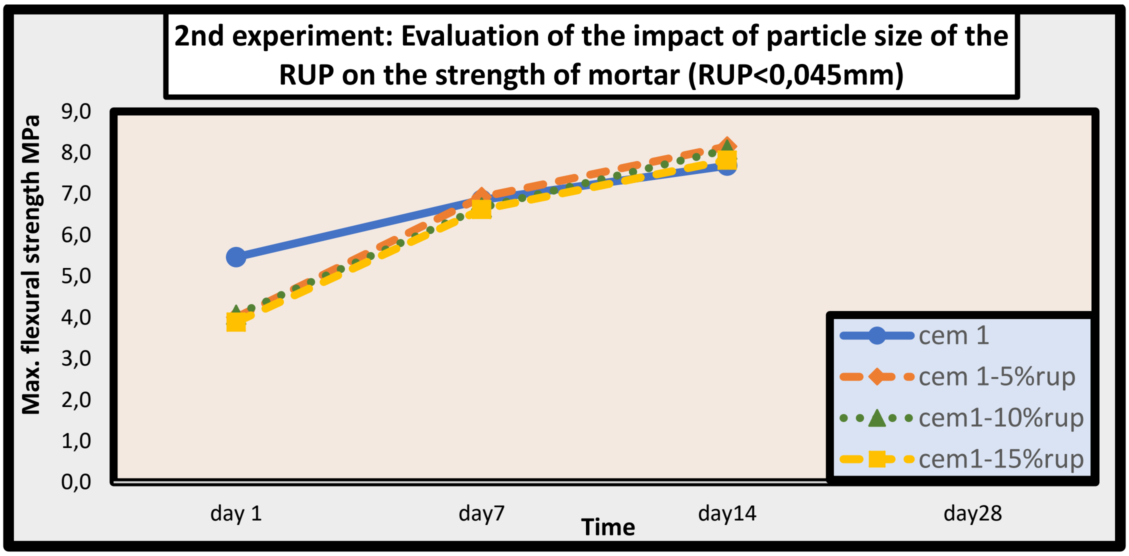

Figure 4.3 The diagram of the flexural strength test of the 2nd experiment

Furthermore, based on the diagram above, there are some important conclusions. At 14 days, mortars with 5, 10 and 15 % replacement of RUP have a bit higher average flexural strength than the reference sample without RUP from the 1st experiment (7,7 MPa). At 14 days the 5%and 10% containing mortars seem to have higher than 8 MPa average flexural strength. This is an exciting performance. The smaller RUP (<0,045) seem to have positive impact and to improve the flexural strength and the elasticity of the mortars in contrast to the RUP below 125 microns from the 1st experiment. This can be explained from the fact that the addition of finer parts decreases the interparticle distance, leading to an increase to the shear between the particles especially during mixing and therefore it raises the dissolved ions into the solution (Mahieux, 2020). This means that the mortars with smaller RUP below 45 microns are more compact than these with RUP below 125 microns leading to higher flexural strength values and increased elasticity.

4.2.3 Mechanical properties - Compressive strength

Another interesting mechanical property that was studied with RUP below 45 microns is the compressive strength of the mortars. These measurements were planned to be accomplished in four different ages 1,7,14 and 28 days respectively for the three mixtures in comparison to the reference sample values from the 1st experiment. Due to covid-19 and the following cancellation of the last age of measurement of the 2nd experiment, there are only measurements of compressive strength for the age 1,7 and 14 day like the flexural strengths before. The lack of the measurements of 28 days creates a problem in the conclusions. But these measurements can give some useful points and an interesting forecast about the usage of recycled ultrafine particles in concrete section. The Figure 4.4 below depicts with flows the mean values of the compressive strength of the 2nd experiment. Also, the Table F in the Appendices shows in detail the average compressive strength for all the samples per day of measurement for the 2nd experiment.

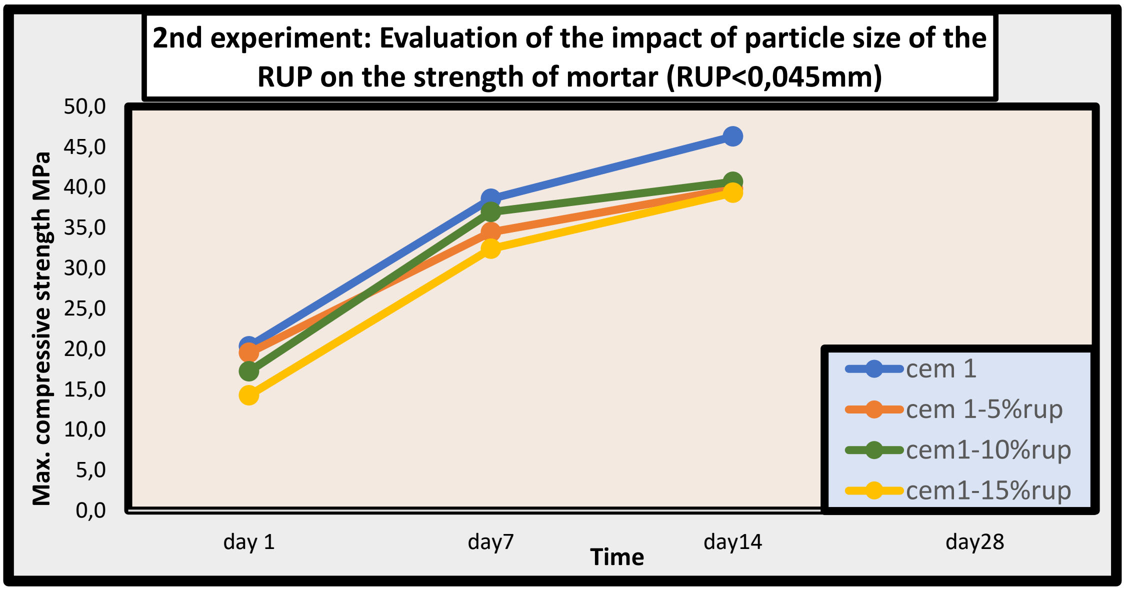

Figure 4.4 The diagram of the compressive strength test of the 2nd experiment

Based on the above results, there are some useful findings on the compressive strengths in the 2nd experiment. From the 1st experiment, the CEM1 reference mortar samples have an average compressive strength of about 21,4 MPa in the day1, 38,6 MPa in the day 7 and 46,3 MPa in the day14, which it was the higher value of all in the 1st experiment and in the 2nd experiment. The CEM1-5%RUP mortar samples have average compressive strength of about 22,4 MPa in the day1, which it increases during the other measurements of the next days with 34,5 MPa in the day 7 and 39,8 MPa in the day14. Moreover, the CEM1-10%RUP and the CEM1-15%RUP mortar samples have satisfactory average compressive strength in comparison to the high values of the reference samples. The first has about 17,2 MPa in the day1, which it enhances during the other measurements of the next days with 37 MPa in the day 7 and 40,7 MPa in the day14.The CEM1-15%RUP mortar samples have an average compressive strength of about 14,3 MPa in the day1, which it has a great enhancement in the next ages with 32,4 MPa in the day 7 and 39,3 MPa in the day14.

Furthermore, some critical points are also indicated. Initially, at 14 days the reference mortar seems to have higher compressive strength than the RUP containing mortars. The decrease of the average compressive strengths in the RUP (5,10,15%) containing mortars range from 14% to 17%. This is a considerable decrease for the new mortars. Although this notable reduction, the average compressive strengths of mortars with RUP below 45 microns are satisfactory, approximately 40 MPa for all of them. Moreover, as the days of the measurements goes by, the average compressive strengths of all mortars incline to higher values. Finally, a general observation about this diagram is that the results are still satisfactory, with the average compressive strengths of the mortars with RUP below 45 microns being relatively high. In addition to this, CEM1-10%RUP and CEM1-15%RUP seem to have better performance regarding the average compressive strength with the milled RUP than them below 125 microns. Hence, there is a positive impact of smaller size on the compressive strength of mortars in the higher replacement ratios. One potential reason is the filler effect in mortar/concrete production. Finely ground mineral powders are known to accelerate cement hydration rates. This "filler effect" has been attributed to the effects of dilution (w/c increase) when the cement content is reduced or to the provision of additional surface area by fine powders. The latter contribution (i.e., surface area increase-high surface area) is speculated to provide additional sites for the nucleation of the hydration products, which accelerates reactions making these smaller particles more efficient (Rates, 2013). This filler effect can complete the particles arrangement of cement and thus improve its packing density leading to more compactness of mortar/concrete (Mahieux, 2020). Also, the addition of finer parts of RUP decreases the interparticle distance, leading to an increase to the shear between the particles especially during mixing and therefore it raises the dissolved ions into the solution (Mahieux, 2020). This means that the mortars with smaller RUP below 45 microns have greater compaction than these with RUP below 125 microns leading to higher compressive strength values.

4.3 Impact of recycled sand

The 3rd experiment includes the formulation of a new mortar recipe that incorporates recycled sand and recycled ultrafine particles. For this purpose, in this experiment, recycled sand was used totally instead of natural sand (100 % replacement ratio). The target is the assessment of the impact of recycled sand in production of new innovative mortars. In the next sections, the workability of fresh mortars as well as the flexural and compressive strengths are tested.

4.3.1 Workability of fresh mortar

The workability of fresh mortar for the 3rd experiment was checked by the accomplishment of the slump test in the lab. The slump values of the mortars containing recycled sand instead of natural with or without RUP were compared with values of the reference mixture from the 1st experiment. For the 3rd experiment, the results of the slump test are shown in the Table 4.3 below:

slump test				
	measurement diameters (cm)		mean (cm)	deviation 1st/2nd %
CEM 1	17,8	18	17,9	0,56/0,56
CEM 1-RS	20	19,4	19,7	1,52/1,52
CEM 1-5%RUP-RS	21	22	21,5	2,32/2,32
CEM1-10%RUP-RS	22,5	23,5	23	2,17/2,17
CEM1-15%RUP-RS	25	24,4	24,7	1,22/1,22

Table 4.3 Results of slump test of the 3rd experiment

The results in the figure above reveal that the deviation of the four mixtures are less than 10%. Consequently, the mean value of the measurements of the two angles can be used as flow values. The mixture CEM1-15%RUP-RS have the higher slump values with 24,7 cm. Also, the mixtures CEM1-10%RUP-RS and CEM1-5%RUP-RS have high slump with 23 cm and 21,5 cm respectively. The mixture CEM1-RS has average slump value 19,7 cm and the reference sample has 17,9 cm.

The preparation of the 3rd experiment indicated that there was a need for water compensation to the samples before the mixing, because the recycled sand and especially combined with RUP have very high water absorption capacity leading to very dry mixtures and zero slump in the training attempts. The addition of 400ml of extra water in the mixtures has as a result relatively big w/b and w/c ratios that obviously affect the slump test and the workability of the fresh mortar. According to the Table 4.3, as the substitution rate of RUP increases, the mean flow value is enhanced, so higher fresh-state workability. Before the 3rd experiment, it was thought that the reference sample would have higher mean slump value than the new mortars with recycled sand and RUP below 125 microns due to the higher water absorption capacity of recycled sand particles than natural sand particles (Zhao et al., 2015). Hence, the mortars with recycled sand and RUP should have lower average slump value than the reference one mortars. But there is an argument for this reverse observation. Due the total replacement of natural sand of with recycled sand (the high water absorption of recycled sand was compensated with extra water) in the new mortars and the addition of extra water, the w/c ratio and the w/b ratio of the mixtures are increased, as the substitution rate also raises. Hence, there is a creation of excess of water that contributes to the higher slump values. Also, the theoretical amount of absorbed water is added at the beginning of mixing leading to a temporary increase of the initial efficient w/c ratio and volume of paste, leading to a better workability before its absorption into RS particles (Zhao et al., 2015) . This increase of the w/c ratio can deal with the disadvantage of the recycled sand, that they have bigger water absorption capacity leading to satisfactory results for the slump test in this experiment.

4.3.2 Mechanical properties -Flexural strength

Flexural strength is an important mechanical property for mortar/concrete production. It was measured also for the 3rd experiment of this MSc thesis for studying the impact of recycled sand in the mortars instead of natural sand. It was supposed that four different ages; 1,7,14 and 28 days would take place. But due to the worldwide outbreak of covid-19 and the following cancellation of the last two days of measurement of the 3rd experiment, there are only measurements of flexural strength for the 1 and 7 days. One measurement less in contrast to 1st and 2nd experiment, that makes the situation difficult for clear conclusions. At least these two days of measurements can give some important observations and useful forecast for the presence of recycled sand in such mixtures. The diagram in Figure 4.5 below shows with flows the mean values of the flexural strength of the 3rd experiment. Moreover, the Table G in the Appendices analyses thoroughly the average flexural strength for all the samples per day of measurement.

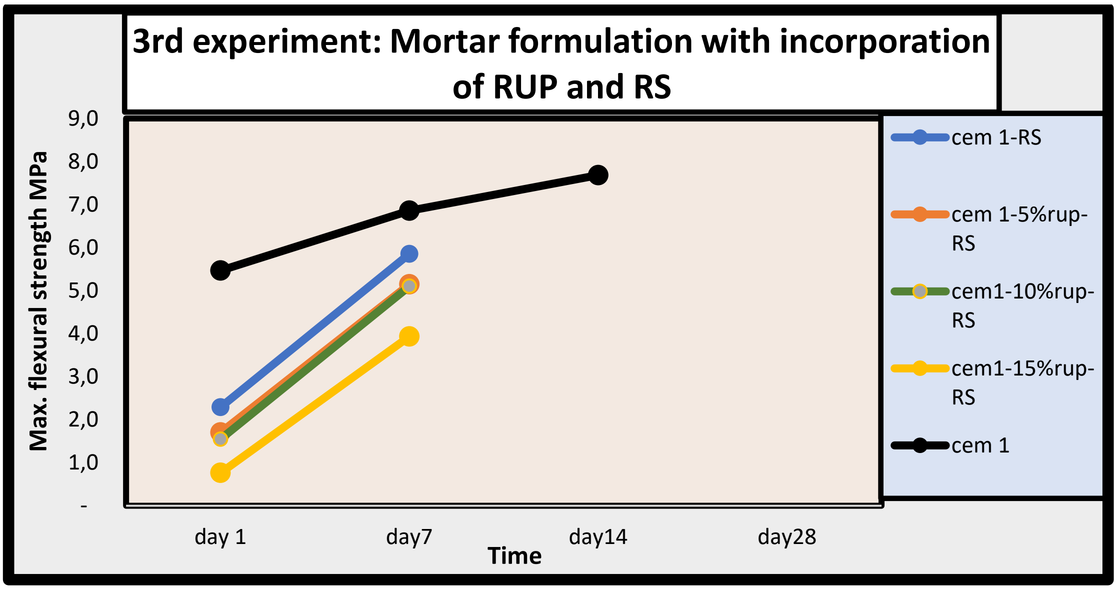

Figure 4.5 The diagram of the flexural strength test of the 3rd experiment

In the diagram above, the CEM1 reference mortar samples from the 1st experiment have the highest average flexural strength of about 6,9 MPa in the day 7 and 7,7 MPa in the day14. The CEM 1-RS with only recycled sand instead of natural and without RUP have the highest average flexural strength among the mortars with recycled sand with 5,9 MPa in the day7. The CEM1-5%RUP-RS and CEM1-10%RUP-RS mortar samples have similar average flexural strength of 5,1 MPa in the day 7. Finally, the CEM1-15%RUP-RS mortar samples have an average flexural strength of about 4 MPa in the day7.

Furthermore, based on the diagram above, there are some critical points for the influence of the usage of recycled sand in the mortars. Initially, the presence of recycled sand instead of natural sand seem to reduce the flexural strength of mortars with this 100% substitution. Furthermore, the combination of recycled sand with RUP seem to decrease the average values of the flexural strength. The major reason for this observation is the very high water absorptivity of the recycled materials despite the compensation with the extra water and the increased w/c and w/b ratio. The results seem to be discouraging. These measurements of flexural strength conclude to the facts that the total replacement of natural sand with recycled sand and the quantity of the extra water affect significantly the 3rd experiment. Obviously, smaller replacement rate than 100% of natural sand with recycled sand and different quantity of water compensation could improve the measurements of flexural strengths.

4.3.3 Mechanical properties - Compressive strength

Another vital mechanical property that was studied with recycled sand and RUP below 125 microns is the compressive strength of the new mortars. These measurements were planned to be accomplished in four different ages 1,7,14 and 28 days respectively. But due to the worldwide outbreak of covid-19 and the following cancellation of the last two days of measurement of the 3rd experiment, there are only measurements of flexural strength for the 1 and 7 days. There is one less measurement in contradiction to 1st and 2nd experiment leading to difficulties for conclusions. But these results could give some an interesting forecast about the usage of recycled sand in combination with recycled ultrafine particles in concrete section. Figure 4.6 shows with flows the mean values of the compressive strength of the 2nd experiment. Also, the Table H in the Appendices reveals in detail the average compressive strength for all the samples per day of measurement for the 3rd experiment.

There are some important findings on the compressive strengths in the 3rd experiment according to the figure below. The CEM1 reference mortar samples from the 1st experiment have the highest average compressive strength of about 38,6 MPa in the day 7 and 46,3 MPa in the day14, which it was the highest value of all the experiments. The CEM1-RS mortar samples have average compressive strength of about 22,6 MPa in the day7. The CEM1-5%RUP-RS mortar samples have average compressive strength 20,5 MPa in the day7. Moreover, the CEM1-10%RUP-RS has 16,8 MPa in the day7 and the CEM1-15%RUP mortar samples have the lowest average compressive strength with 13,7 MPa in the day7.

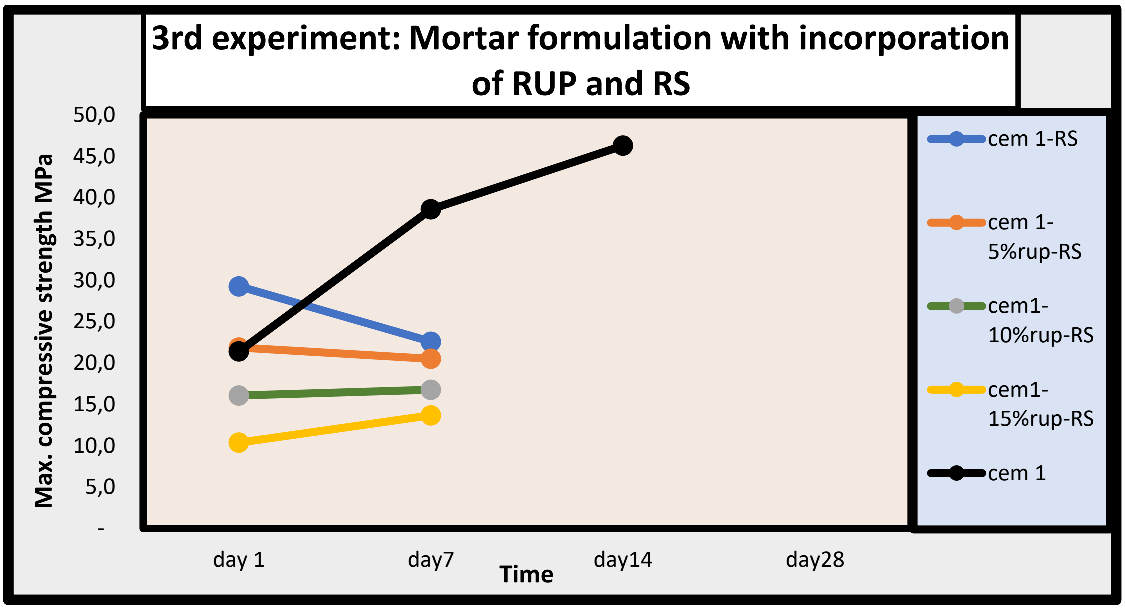

Figure 4.6 The diagram of the compressive strength test of the 3rd experiment

Moreover, some crucial points are revealed from this diagram for the effect of the usage of recycled sand in the mortars regarding the compressive strengths. Initially, the usage of recycled sand instead of natural sand decrease the compressive strength of mortars with this 100% substitution. Furthermore, the combination of recycled sand with RUP seem to decrease the average values of the compressive strength more. As the replacement ratio of RUP in combination with recycled sand, the compressive strength decreases. Lower compressive strength means lower durability for the mortars with the RS particles. Some possible reasons for this notable reduction are some characteristics mainly of recycled sand particles in contrast to natural particles:

- RS can create problems to the mechanical properties of mortars due to the higher water absorption (RS particles induce a large water demand) and the adherent cement paste content. Also, this presence of adherent cement paste can lead to higher porosity and water absorption (Zhao et al., 2015).
- Another factor can be the origin of the RS used. The fine recycled particles produced from crushed concrete or directly from construction and demolition waste (CDW) have distinct characteristics that affect the mortar/concrete made with them in very dissimilar ways (Evangelista & Brito, 2014).
- It is generally thought that the particle density and loose bulk density of RS particles are lower than those of FNA. The main reason for this is that the fine recycled grade can contain mortar, from either crushed concrete or some remaining residues from other non-stone contaminants such as brick, gypsum or wood. Consequently, the water absorption of recycled fine aggregates is higher than that of FNA, which is, in fact, the physical characteristic that differs the most (Evangelista & Brito, 2014).

- The decreased loose bulk density demonstrates the higher degree of angularity of the RS particles. The sphericity also varied more confirming the previous statement (Evangelista & Brito, 2014).

Furthermore, at very young age of 1 day (very fresh mortar), mortars with RS and with RS+5% RUP have great performance, higher compressive strengths than the reference sample, maybe due to the water compensation. The early stage hydration seems high for this recipe. As the time increases, the mortars with recycled sand seem not to gain a lot compressive strength. The gain in strength over time was poor. Hence, this 3rd experiment shows that mortars with recycled sand have very good performance regarding the compressive strengths as fresh mortars but not in the next ages. All the data indicate as major factor the high water absorptivity of the recycled materials which leads to the less bonding between cement matrix and water, although the extra water and the increased w/c and w/b ratio. Finally, smaller replacement rate than 100% of natural sand with recycled sand and different quantity of extra water could lead to better results for compressive strengths.

4.4 Comparison of the mechanical properties for mortars with different size RUP

In this paragraph, there is a presentation of the comparison of the results between the 1st and 2nd experiments and especially regarding the mechanical properties of mortars with RUP below 45 and 125 microns respectively. Each figure depicts another substitution percentage of cement with recycled ultrafine particles, the blue lines for 1st experiment with recycled ultrafine particles below 125 microns and the green lines for 2nd experiment with particles below 45 microns. Hence, this comparison has as a target to show the role of the size of recycled cement paste particles. Also, all the diagrams include the CEM1 reference sample with the black line to have a simultaneous contrast with the average reference values regarding flexural and compressive strengths for 1,7 and 14 days respectively.

In the Figure 4.7 below, it is depicted the average flexural strength for the samples with 5% replacement of cement with recycled ultrafine particles, below 125 microns for blue line of the 1st experiment and below 45 microns for green line of 2nd experiment. According to this figure, both mortars with 5% replacement of cement with recycled cement paste have higher average flexural strength than the reference sample. The two performances seem to be exciting. The dark blue line of the 1st experiment reaches almost at 9 MPa of average flexural strength and green line of the 2nd experiment has higher average flexural than 8 MPa and higher than 7,7 MPa of the reference sample. Hence, at 5% replacement ratio of cement with RUP, it seems that the average flexural strength has an increase at 14 days. It is a useful forecast for 5% substitution ratio regarding the flexural strengths and its effectiveness in mortar/concrete production.

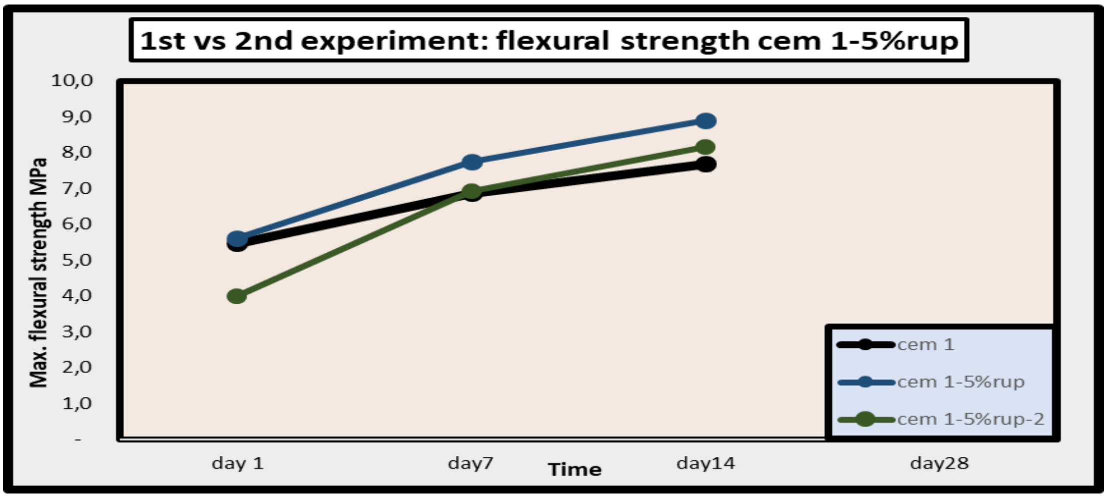

Figure 4.7 Comparison of flexural strength between 1st vs 2nd experiment for 5% substitution with RUP

In the Figure 4.8 below, it is depicted the average flexural strength for the samples with 10% replacement of cement with recycled ultrafine particles, below 125 microns for blue line of the 1st experiment and below 45 microns for green line of 2nd experiment.

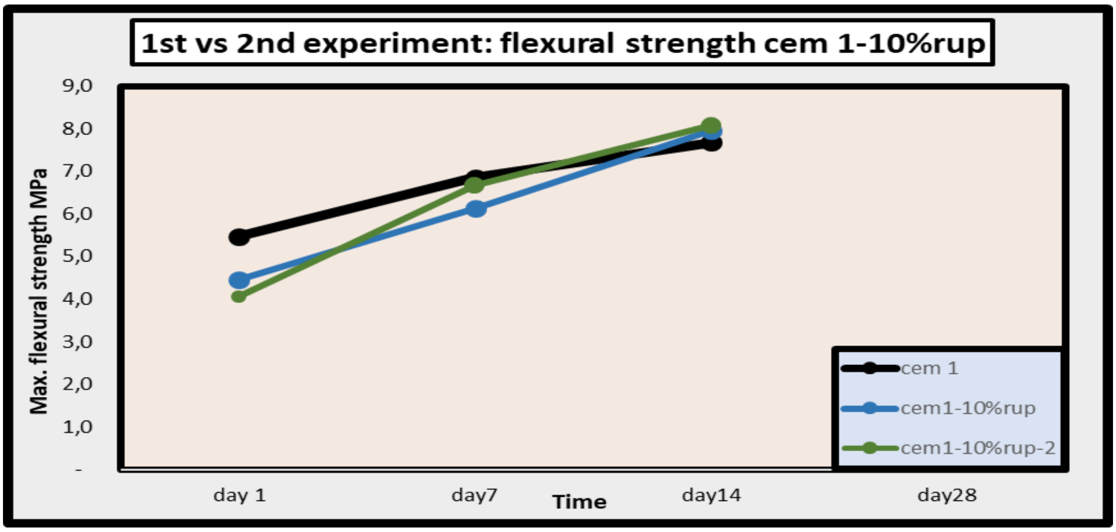

Figure 4.8 Comparison of flexural strength between 1st vs 2nd experiment for 10% substitution with RUP

According the figure above, both mortars with 10% replacement of cement with recycled cement past have slightly higher average flexural strength than the reference sample. The two performances seem to reach about 8MPa. The blue line of the 1st experiment reaches exactly at 8 MPa of average flexural strength at 14 days and green line of the 2nd experiment has higher average flexural than 8 MPa (8,1 MPa) and higher than 7,7 MPa of the reference sample. Hence, at 10% replacement ratio of cement with

RUP, it seems that the average flexural strength has an increase at 14 days for both mortars and similar performance; a bit better for the mortar of the 2nd experiment. It is an important forecast for 10% replacement ratio regarding the flexural strengths and the utility of recycled cement paste for reuse in mortar/concrete production.

In the Figure 4.9 below, it is depicted the average flexural strength for the samples with 15% replacement of cement with recycled ultrafine particles, below 125 microns for blue line of the 1st experiment and below 45 microns for green line of 2nd experiment.

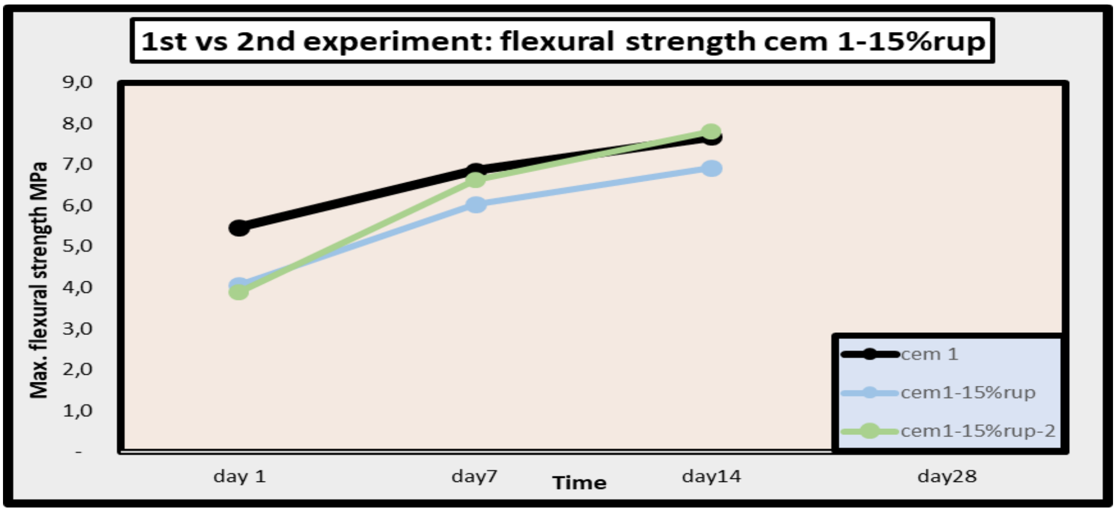

Figure 4.9 Comparison of flexural strength between 1st vs 2nd experiment for 15% substitution with RUP

According the figure above, mortar with 15% replacement of cement with recycled cement from the 2nd experiment past has slightly higher average flexural strength than the reference sample close to 8MPa. The blue line of the 1st experiment reaches almost at 7 MPa of average flexural strength at 14 days. It means that it has an enough performance, relatively close to 7,7 MPa of the reference sample. Hence, at 15% replacement ratio of cement with RUP, it seems that the average flexural strength has an increase at 14 days for the mortars with smaller size of recycled cement paste particles of the 2nd experiment. It is an important forecast for 15% replacement ratio regarding the flexural strengths and the effectiveness of the smaller particles below 45 microns as the substitution rate of RUP increases. It seems that the smaller particles are constantly more efficient than the bigger ones, especially at higher replacement rates.

In the Figure 4.10 below, it is depicted the average compressive strength for the samples with 5% replacement of cement with recycled ultrafine particles, below 125 microns for blue line of the 1st experiment and below 45 microns for green line of 2nd experiment.

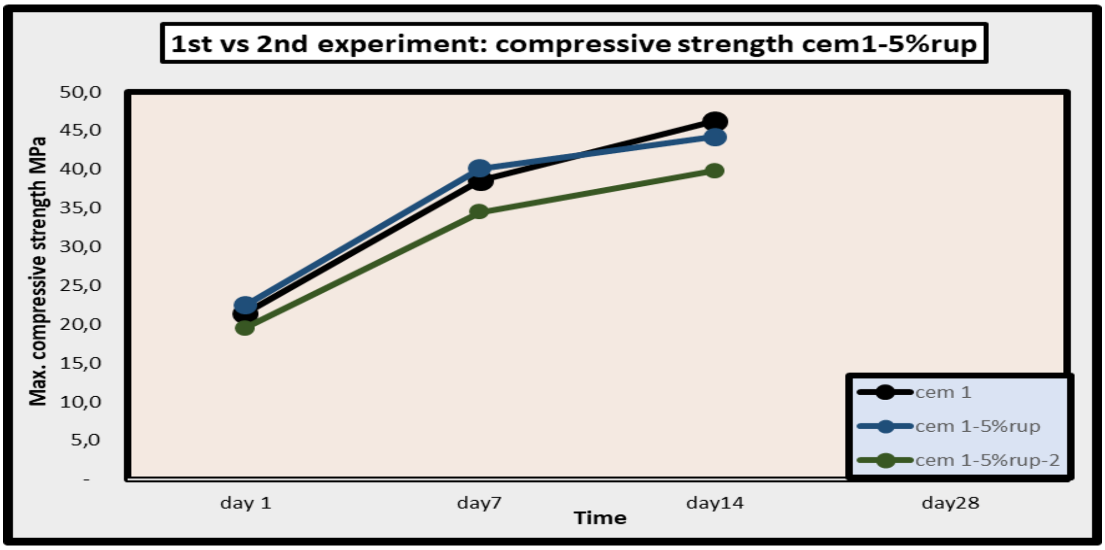

Figure 4.10 Comparison of compressive strength between 1st vs 2nd experiment for 5% substitution with RUP

Regarding the figure above, mortars with 5% replacement of cement with recycled cement paste from the 1st experiment has high average compressive strength with almost 45MPa close to the value of the reference sample at 14days. The dark green line of the 2nd experiment has average compressive strength about 40 MPa at 14 days. It seems also good performance. Hence, at 5% replacement ratio of cement with RUP, the average compressive strength of the two experiments is enough at 14 days with 45 MPa and 40 MPa respectively. It is a useful forecast for 5% substitution ratio samples regarding the compressive strengths and their effectiveness in mortar/concrete production. At 5% substitution rates, the diagrams show that the size of the recycled ultrafine particles does not play a crucial role regarding the compressive strengths.

In the Figure 4.11 below, the average compressive strength for the samples with 10% replacement of cement with recycled ultrafine particles is depicted, for below 125 microns with the blue line of the 1st experiment and for below 45 microns with the green line of the 2nd experiment.

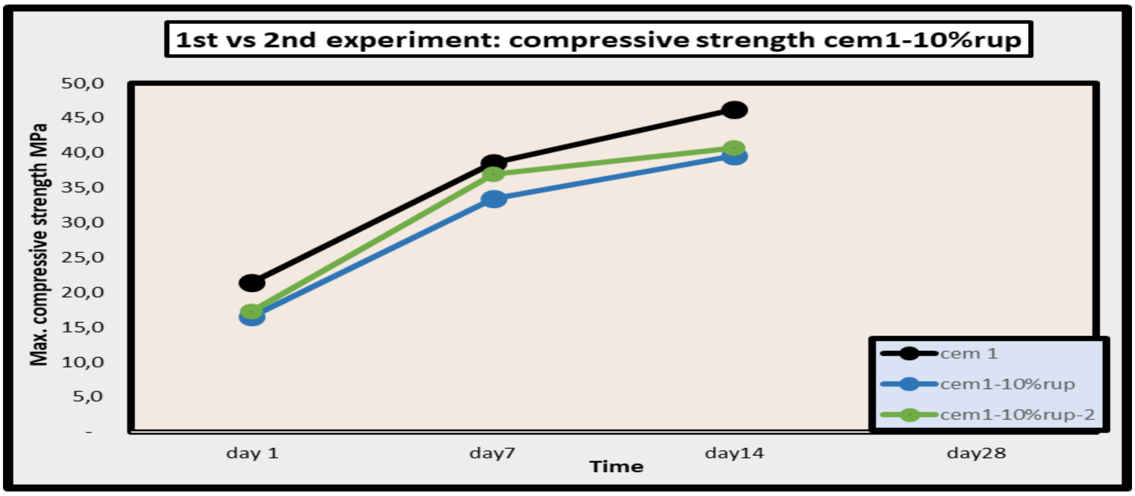

Figure 4.11 Comparison of compressive strength between 1st vs 2nd experiment for 10% substitution with RUP

According the figure above, mortars with 10% replacement of cement with recycled cement paste from both experiments have great average compressive strength with approximately 40MPa close to the value of the reference sample at 14 days. The dark green line of the 2nd experiment has higher average compressive strength than this from the 1st experiment with 40,7 MPa at 14 days in contrast to the lower for bigger particles with 39,5 MPa. It seems also good performance. Hence, at 10% replacement ratio of cement with RUP, the average compressive strength of the two experiments shows very good performance. It is a significant forecast for 10% substitution ratio samples regarding the compressive strengths and their effectiveness in mortar/concrete production. At 10% substitution rates, the diagrams show that the smaller size of the recycled ultrafine particles contribute to better values of average compressive strengths.

In the Figure 4.12 below, the average compressive strength for the samples with 15% replacement of cement with recycled ultrafine particles is depicted, for below 125 microns with the blue line of the 1st experiment and for below 45 microns with the green line of the 2nd experiment.

According the figure below, mortars with 15% replacement of cement with recycled cement paste from both experiments have great average compressive strength with almost 40 MPa close to the value of the reference sample at 14 days. The dark green line of the 2nd experiment has higher average compressive strength than this from the 1st experiment with 39,3 MPa at 14 days in contrast to the lower for bigger particles with 38,4 MPa. Hence, at 15% replacement ratio of cement with RUP, the average compressive strength of the two experiments shows great performance at 14 days. It is a significant forecast for 15% substitution ratio samples regarding the compressive strengths and their usage in mortar/concrete samples. At 15% substitution rates, the diagrams show that the smaller size of the recycled ultrafine particles leads to better values of average compressive strengths.

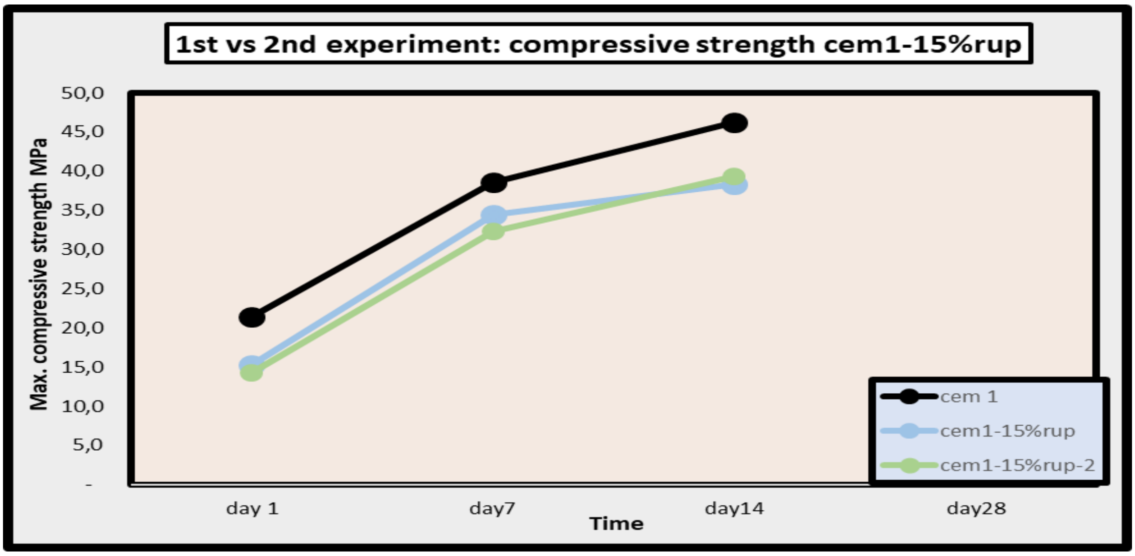

Figure 4.12 Comparison of compressive strength between 1st vs 2nd experiment for 15% substitution with RUP

Obviously, the conclusion from the diagrams is that the samples from the 2nd experiment with the smaller particles show more constant performance regarding the average compressive strengths. As the replacement ratio of the recycled ultrafine particles in the mortar is increased, sample with RUP below 45 microns have better results in contrast to them with RUP below 125 microns, which their average compressive strengths decrease when the replacement ratio enhances. It should be mentioned that all the values are close to them from the reference sample and that leads to satisfying results regarding the compressive strengths.

4.5 Relationship between w/c ratio, slump and mechanical properties in mortars with different size RUP

4.5.1 Relationship between w/c ratio, slump and mechanical properties in mortars with RUP below 125 microns

In this section it is investigated the relationship between w/c ratio, slump and mechanical properties like flexural and compressive strength in the 1st experiment with RUP below 125 microns as partial replacement of cement. The three following diagrams depict this relationship. The Figure 4.13 describes the results of the slump test in function of w/c ratio of the mixtures. The Figures 4.14 and 4.15 indicate the relationship between the flexural and compressive strength and the w/c ratio in the mixtures for the three different days of measurements; 1,7 and 14 day.

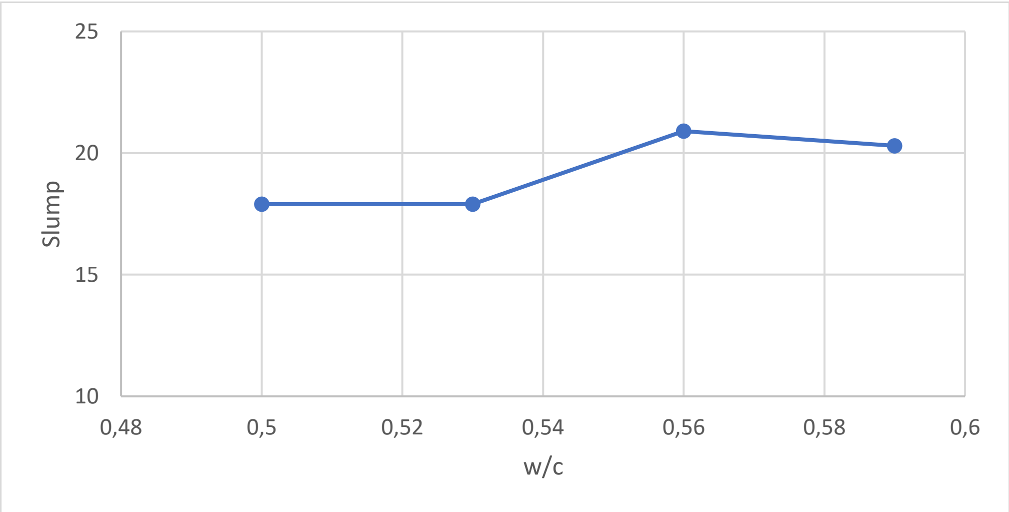

Figure 4.13 Relationship between slump and w/c of mortars with RUP below 125 microns

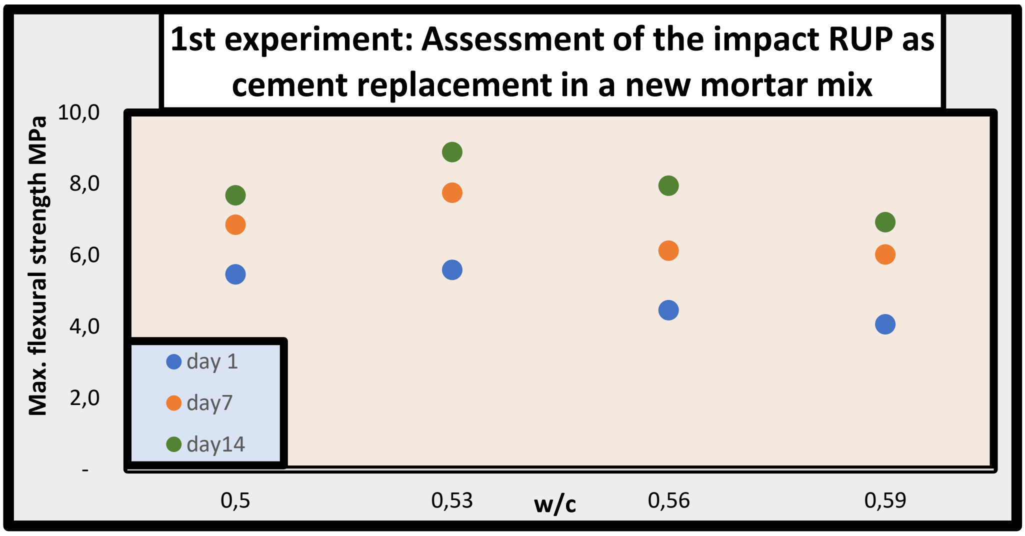

Figure 4.14 Relationship between flexural strength and w/c of mortars with RUP below 125 microns

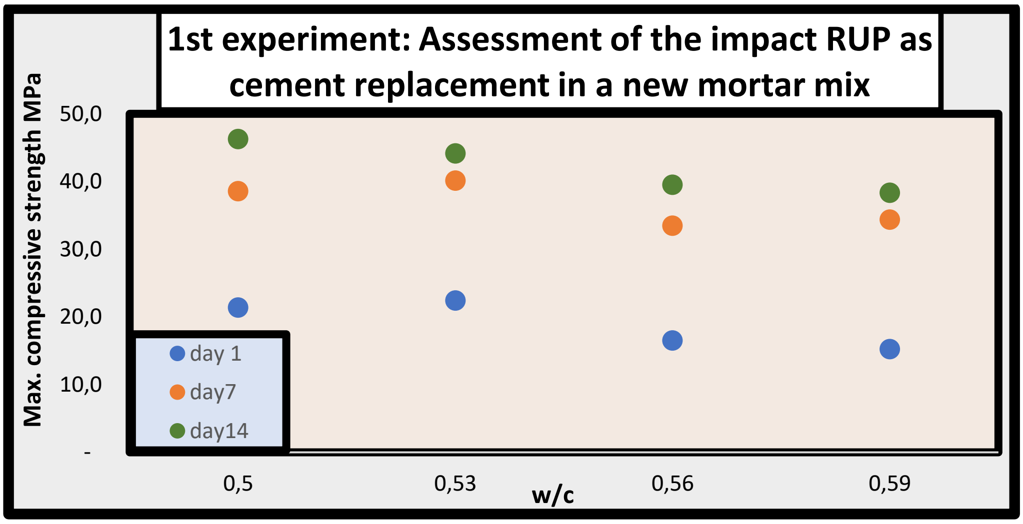

Figure 4.15 Relationship between compressive strength and w/c of mortars with RUP below 125 microns

The Figure 4.13 indicates that the increase of the w/c ratio in the 1st experiment leads to higher values of slump in the mortar mixtures. The peak of slump is at 0,56 of w/c ratio. It seems that this excess of water and the increased w/c ratio lead to more available water that makes the mortar fluid. Hence, the w/c ratio improves the fresh-state workability of the mortars.

The Figure 4.14 shows that the peak of flexural strength for all mortars is at 0,53 of w/c ratio for all the days of the measurements. It does not seem according to the diagram that there is a specific relationship between the flexural strength and the w/c ratio. Also, it is obvious that in the 14 days the flexural strength of all the mortars with RUP below 125 is better or close to the reference one.

In the Figure 4.15 it is depicted the relationship between the compressive strength of the mortars and the w/c ratio. It seems that as the w/c ratio of the mortars is enhanced, the performance regarding the compressive strength is decreased for all the days of the measurements. The increased w/c ratio in combination with the increased replacement ratio with RUP below 125 microns reduce the compressive strength of the mortars.

4.5.2 Relationship between w/c ratio, slump and mechanical properties in mortars with RUP below 45 microns

The section 4.5.2 reveals the relationship between w/c ratio, slump and mechanical properties like flexural and compressive strength in the 2nd experiment with milled RUP below 45 microns as partial replacement of cement. This relationship is depicted in the three diagrams below. The results of the slump test in function of w/c ratio of the mixtures is depicted in the Figure 4.16. The Figures 4.17 and 4.18 show the relationship between the flexural and compressive strength and the w/c ratio in the mixtures for the three different days of measurements; 1,7 and 14 day.

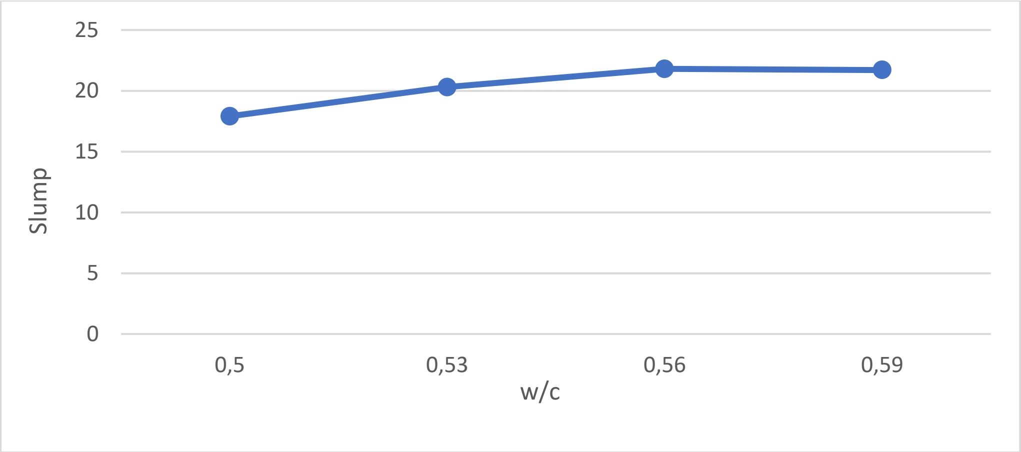

Figure 4.16 Relationship between slump and w/c of mortars with RUP below 45 microns

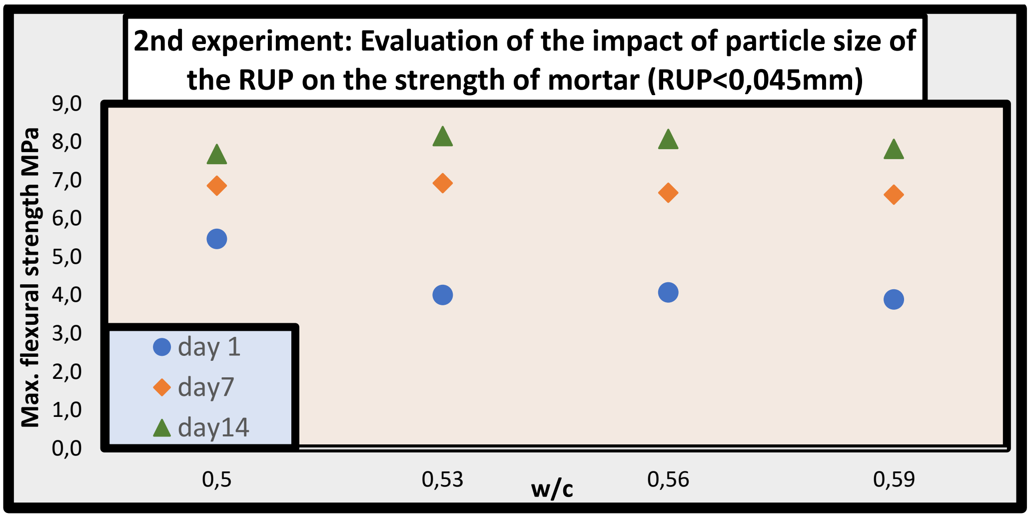

Figure 4.17 Relationship between flexural strength and w/c of mortars with RUP below 45 microns

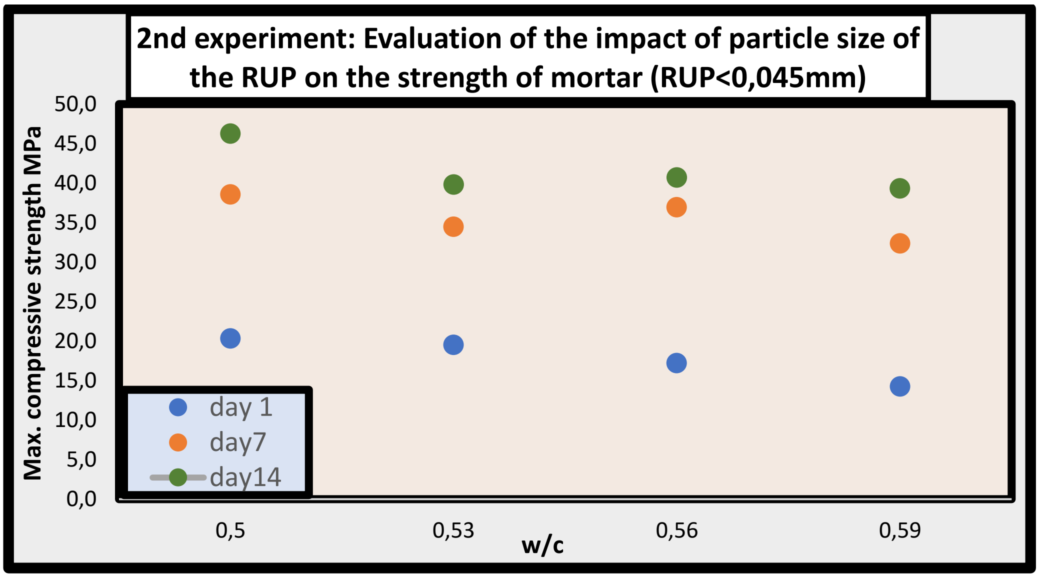

Figure 4.18 Relationship between compressive strength and w/c of mortars with RUP below 45 microns

In the Figure 4.16 it is revealed that the increase of the w/c ratio in the 2nd experiment leads to higher values of slump in the mortar mixtures. The higher the w/c ratio of the mixtures, the higher the value of the slump is. It seems that the increased w/c ratio improves the slump value of the mortars with RUP below 45 microns.

The Figure 4.17 depicts that the peak of flexural strength for all mortars is at 0,53 of w/c ratio for the 7 and 14 days of the measurements. It does not seem according to the diagram that there is a specific relationship between the flexural strength and the w/c ratio. For all the days of the measurements and especially at 14 day the average flexural strength of the new mortars with milled RUP below 45 is better from the reference one. The increased w/c ratio and smaller size of the RUP seem to improve the performance regarding the flexural strength in satisfactory level.

The Figure 4.18 shows the relationship between the compressive strength of the mortars with RUP below 0,045 mm and the w/c ratio. It seems that the higher than 0,5 w/c ratio of the mortars provokes lower compressive strength for all the days of the measurements. But the situation is more balanced in contrast to the respective diagram of the bigger RUP. The smaller size of RUP results to better compressive strengths. The increased w/c does not help the performance of the new mortars regarding compressive strength.

4.6 Conclusion for the results of the experiments

In the previous paragraphs, there was an analysis of the experimental phase and especially for experiments 1,2,3. From each separate analysis for all the experiments and the comparison between the 1st and the 2nd experiment some useful conclusions are drawn and can be used as useful forecast to examine the effect of recycled cement paste and recycled sand in mortar/concrete manufacture.

Some crucial points are presented below, that could be used for further study in the field of recycled materials and especially the effectiveness of recycled ultrafine materials and their future usage:

- Regarding the slump of the mortars, slumps with RUP are higher than the reference one. RUP (0,125 mm and 0,045mm) can lead to enhancement of the slump value with the contribution of the increased w/c ratio (excess of water) for the 1st and the 2nd experiment at any substitution rate. The similar conclusion can be revealed for the slump of the 3rd experiment with the compensation of extra water, which leads to increased w/c and w/b ratio, and these data help the slump value at any replacement ratio. Due to the reduction of cement quantity and its replacement with RUP in the new mortars, the w/c ratio of the mixtures is increased, as the substitution rate also is enhanced. This excess of water can contribute to higher slump values. Also, the packing density tends to increase with the cement substitution with RUP. This may be explained by a better arrangement of the solid particles. This information can be combined with observations for slump in the experiments with RUP substitution. Indeed, with an increasing packing density, the amount of water needed to fill the porosity decreases and more water is available to make the mortar fluid (Mahieux, 2020). In the experiment with RS, the w/b ratio also is enhanced due to the extra water compensation. Hence, there is a creation of excess of water that contributes to the higher slump values. Also, the theoretical amount of absorbed water is added at the beginning of mixing leading to a temporary increase of the initial efficient w/c ratio and volume of paste, leading to a better workability before its absorption into RS particles (Zhao et al., 2015) This increase of the w/c ratio can counterbalance the disadvantage of the RS particles that they have higher water absorption capacity, leading to similar or better results for the slump test of the fresh mortars in contrast to the reference sample. Hence, the excess water in the experiments had probably a crucial role in the demonstration of these results with increased fresh-state workability.

- Regarding the general impact of RUP in mortar/concrete production with the results from the 1st experiment, the replacement with 5 and 10% of cement with RUP can increase the performance of mortar regarding the flexural strength, leading to better resistance to deformation under bending. The replacement with 15 % or over with RUP seems to decrease slightly the performance of mortar regarding the flexural strength. At young ages of 1 and 7 days, mortar with 5% RUP has higher average compressive strength than the reference sample value. As the time increases, the compressive strength of all mortars is increased but in 14 days there is a notable reduction. This can be explained by the effect of acceleration of cement hydration and increase of hydraulic reactivity of cement due to presence of RUP and their higher specific area (Mahieux, 2020). Moreover, the recycled materials have some other different features in contrast to the natural ones like the cement particles and these characteristics can be possible reasons for this decrease in compressive strengths of new mortars. RUP below 125 microns have higher water absorption than natural aggregates (Zhao et al., 2015). Furthermore, the compressive strength of mortar/concrete can be affected by the substitution level of RUP; higher replacement ratios mean lower compressive strengths and the quality as well as the origin of recycled aggregates (Evangelista & Brito, 2014). In conclusion, the replacement with RUP below 125 microns has satisfactory results especially for flexural strengths, but it shows some problems regarding the compressive strengths.

- There are also important conclusion points about the impact of RUP particle size from the 2nd experiment and its comparison with the results from the 1st experiment. It seems that the smaller particles are constantly more efficient in flexural strengths than the bigger ones, especially at higher replacement rates of RUP. For compressive strengths, as the replacement ratio of the recycled ultrafine particles in the mortar is increased, sample with RUP below 45 microns have better results in contrast to them with RUP below 125 microns. One potential reason is the filler effect in mortar/concrete production. Finely ground mineral powders are known to accelerate cement hydration rates. This “filler effect” has been attributed to the effects of dilution (w/c increase) when the cement content is reduced or to the provision of additional surface area by fine powders. The latter contribution (i.e., surface area increase-high surface area) is speculated to provide additional sites for the nucleation of the hydration products, which accelerates reactions making these smaller particles more efficient (Rates, 2013). This filler effect can complete the particles arrangement of cement and thus improve its packing density leading to more compactness of mortar/concrete (Mahieux, 2020). Also, the addition of finer parts of RUP decreases the interparticle distance, leading to an increase to the shear between the particles especially during mixing and therefore it raises the dissolved ions into the solution (Mahieux, 2020). In conclusion, the mortars with milled RUP are more compact and have higher packing density than these with RUP below 125 microns leading to better mechanical properties.

- Regarding the impact of the recycled sand from the results of the 3rd experiment, the total replacement (100%) with recycled sand instead of natural sand seems to reduce the flexural strength of mortars. The combination of 100% recycled sand with RUP creates very big water absorptivity and less bonding between cement matrix and water. The results for this specific recipe seem to be discouraging.There are several factors that can be indicated for the poor performance of recycled sand particles in contrast to natural ones. RS can create problems to the mechanical properties of mortars due to the higher water absorption (RS particles induce a large water demand) and the adherent cement paste content. Also, this presence of adherent cement paste can lead to higher porosity and water absorption (Zhao et al., 2015). Another factor can be the origin of the RS used. The fine recycled particles produced from crushed concrete or directly from construction and demolition waste (CDW) have distinct characteristics that affect the mortar/concrete made with them in very dissimilar ways (Evangelista & Brito, 2014). The particle density and loose bulk density of RS particles are lower than those of FNA, because they contain mortar. Consequently, the water absorption of recycled fine aggregates is higher than that of FNA, which is, in fact, the physical characteristic that differs the most (Evangelista & Brito, 2014). The decreased loose bulk density demonstrates the higher degree of angularity of the RS particles. The sphericity also varied more confirming the previous statement (Evangelista & Brito, 2014). It is recommended that amount of recycled sand that replaced natural should be less in the future experiments leading to better mechanical properties. The 100% substitution was very optimistic, because recycled sand particles have very high water absorption capacity (Zhao et al., 2015) and in combination with RUP provoke acceleration in reaction. Also, the amount of water is very crucial. The right quantity can prevent from the zero slump and simultaneously from the early stage hydration helping the mortars to gain flexural and compressive strength over time. All the findings from these 2 ages of measurements for recycled sand in this experimental study can help for further study in future researches.

Chapter 5

Ecological and Economic analysis

The chapter 5 includes the Ecological and Economic approach of the object of the research and answers to the 2nd and 3rd research questions respectively. Apart from the technical feasibility of the research, it is important to study the potential ecological benefits and the market of the new recycled materials like the RUP, the recycled aggregates and the mortars that produced with them. It will be investigated in this paragraph if the combination of all these recycled materials can lead to a potential sustainable development and circular economy in mortar/ concrete production. The sustainability is a chain, it is consisted of many parameters like the humans, the environment, the society, the resources and the market according to chapter 1. Hence, the aim is to make a significant evidence that the usage of RUP in mortar and concrete manufacture can cause benefits for the environment and can create a new market and/or affect the old one leading to a circular economy and sustainable development. This chapter first deals with the ecological benefits from the usage of RUP and then with economic view of a potential market for all the recycled materials.

The analysis of these definitions below will lead the better comprehension of ecological and economic analysis of this research:

Sustainable development: It is the idea that human societies must live and meet their needs without compromising the ability of future generations to meet their own needs. Sustainability is often thought of as a long-term goal, while sustainable development refers to the many processes and pathways to achieve it. The four main types of sustainability are human, social, economic and environmental (Goodland & Bank, 2002). Hence, through the 2nd research question and ecological analysis, the environmental parameter of the potential sustainable development with the use of RUP in mortar/concrete production will be investigated. Furthermore, through the 3rd research question and economic analysis, the economic parameter of the potential sustainable development with the reuse of recycled materials in mortar/concrete production will be investigated.

Green development: is a real estate development concept that carefully considers social and environmental impacts of development. It is defined by three sub-categories: environmental responsiveness, resource efficiency, and community and cultural sensitivity. Environmental responsiveness respects the intrinsic value of nature and minimizes damage to an ecosystem. Resource efficiency refers to the use of fewer resources to conserve energy and the environment (O, Harris, & Goodwin, 2003). The target with the ecological analysis in the 2nd research question is the resource efficiency to be investigated, so the conservation of virgin materials and the environment to be studied.

<u>Circular economy:</u> A circular economy (often referred to simply as "circularity") is an economic system aimed at eliminating waste and the continual use of resources. Circular systems employ reuse, sharing, repair, refurbishment, remanufacturing and recycling to create a closed-loop system, minimizing the use of resource inputs and the creation of waste, pollution and carbon emissions (Nancy & Jan, 2016).

5.1 Ecological analysis

5.1.1 Background on ecology

Cement production is a major source of carbon dioxide, this occurs during the calcination of limestone in the kiln. The amount of carbon dioxide produced is directly proportional to the amount of cement produced. For each ton of cement produced, 0.9 ton of Carbon dioxide is released (Mahasenan, Smith & Humphreys, 2003).

According to some studies, the procedure of reprocessing the C&D waste in order to produce recycled materials can affect positive the environment. All these environmental benefits depend on the effectiveness of the recycling and the machinery, the source of the materials and the reuse supply chain. These environmental gains can contribute to the following sections:

- Reduced consumption of resources and virgin materials

The replacements of the virgin materials with recycled ones can lead to a sustainable development, making feasible to guarantee resources for the next generations.

- Reduced Quarrying

By decreasing the rate of the quarrying, the costs for amenity and biodiversity will be also decreased.

- Reduced required space for landfill

By reusing the C&D waste, the volume and the size of the waste that conclude to landfill is reduced. This helps also to the reduction of the pollution in the environment and to the more sustainable development.

- Less incineration of C&D waste

By reusing the C&D waste, the volume and the size of the waste that conclude to incineration is reduced leading to less air pollution and less consumption of energy.

- Reduced Greenhouse Gas (GhG) Emissions

A significant benefit of the usage of recycled aggregate is the lower embodied energy in combination with the less transport emissions of CO_2 when the recycled are reused directly to the site of the processing area. The following GhG emissions from the use of the recycled materials has been estimated approximately 4.0 kg CO_2 per ton. This means, that there is a reduction in the emissions that ranges between 22% and 46% in contrast to the traditional procedure and process of virgin materials by quarry (Tam et al., 2018).

There are many studies about the reduction of CO_2 emissions. In one of them, there is an estimation that in order to produce 1 ton of recycled materials only 0.0024 tons of CO_2 is emitted, much decreased in comparison with 0.046 tons of CO_2 during the production of natural aggregates. This respects to a 23-28% reduction in the GHG emissions.

In another study for CO_2 emissions evaluated that for the production of 1 ton natural aggregates 0.046 tons of CO_2 is emitted as compared to 0.0024 tons of CO_2 emitted in the production of 1 ton recycled aggregates (Kavitha, 2018). When compared to natural aggregates, recycled aggregates reduce carbon emission by 23–28%. In USA, other studies have revealed that the reduction in carbon emissions with the production of recycled aggregate reaching almost at 30% than the aggregates produced from virgin materials. The difference in the rate in these studies depend on the methodologies used and local electricity generation factors among the countries (Tam et al., 2018). One example regarding the road constructions, the embodied energy and resulting GhG emissions of its material, it is decreased around 25% (Busari, Adeyanju, Loto, & Ademola, 2019). Another study based on monthly production of 150 tons per month) also concluded to the fact that the use of recycled aggregates has environmental benefits with reduction on the embodied energy about 30% and on CO_2 emissions 60% in contrast to the quarried aggregate from virgin materials (Tam et al., 2018).

In the LCA (Life Cycle Assessment) of recycled materials produced from C&D waste in Southeast Asia that was presented by Hossain et al. He reached to a similar result with the previous researches that he use of the recycled aggregates offered a mitigation to the carbon emissions somewhat above 60% and better results about the savings of non-renewable energy consumption close to 58% with the usage of recycled materials for both coarse and fine aggregates(Hossain, Sun, Lo, & Cheng, 2016).

Another study, this time from Serres et al. revealed the beneficial environmental footprint from the usage of coarse recycled aggregate of 20mm in the concrete manufacture with less consumption of energy and less carbon emissions than the one with natural material with the same size (Serres, Braymand, & Feugeas, 2016).

5.1.2 Assessment of CO_2 emissions in lab experiment

The goal of the 2nd research question is the investigation of the potential ecological advantages from the usage of this new mortar. According to the literature review, the calcination of limestone in cement production in the kiln is a crucial source of CO_2 emission. Hence, there is a possibility to have environmental gains regarding the emission of GHG and especially CO_2 from the substitution of cement with recycled ultrafine materials (RUP).

In this paragraph, there is an evaluation of possible reduction in CO_2 in the lab experiments that were conducted for checking the technical feasibility of RUP in the 1st and 2nd experiments. In these experiments of the research with the water/binder ratio (the ratio of the weight of water to the weight of binder used in a concrete mix) constant at 0.5, there is a possibility to have environmental benefits from the substitution of cement with recycled ultrafine materials.

There is an analysis of the data in the following Table 5.1. In this table, there was a substitution of cement with RUP at 5%, 10% and 15 % respectively in the experimental phase. As, it has been already referred, for each ton of cement produced, 0.9 ton of CO_2 is released, an important point that will help for calculation in the different mixtures in the table. There is an estimation, for the total mixture, so the quantity for each mortar is multiplied by 12, because 12 mortars were created for each mixture in the technical part of 1st and 2nd experiments.

Mortar Pastes	Cement I (kg)	CO_2 Emission (kg)	Recycled ultrafine (kg)	Reduction of CO_2 Emission (kg)	Nr. of samples	Reduction of CO_2 Emission %
CEMI - Ref.	200*12=2400 =2,4	2,4*0,9=2,16	0	0	12	0 %
CEMI - 5% RUP	190*12=2280=2,28	2,28*0,9=2,05	10*12=120=0,12	2,16-2,05=0,11	12	0,11/2,16* 100=5,1%
CEMI - 10%RUP	180*12=2160=2,16	2,16*0,9=1,94	20*12=240=0,24	2,16-1,94=0,22	12	0,22/2,16* 100= 10,2%
CEMI - 15%RUP	170*12=2040=2,04	2,04*0,9=1,84	30*12=360=0,36	2,16-1,84=0,32	12	0,32/2,16* 100= 14,8%

Table 5.1 Reduction of CO_2 emissions in the experimental study

The amount of carbon dioxide produced is directly proportional to the amount of cement produced due to the usage of the factor 0,9 which is close to 1. Also, the percentage of the reduction of carbon emissions in the experiments depends on the level of the substitution of cement with recycled ultrafine materials. Hence, 5 % substitution with RUP leads to 5,1% reduction of CO_2 emissions with 0,11 kg less carbon, 10% substitution with RUP leads to 10,2% reduction of CO_2 emissions with 0,22 kg less carbon and 15 % substitution with RUP leads to 14,8% reduction of CO_2 emissions with 0,32 kg less carbon. It is obvious that yet in this small-scale experiment in the lab, there is a decrease to the environmental footprint with less CO_2 emissions during each experimental phase. This is how the replacement with recycled ultrafine can be environmentally friendly in small scale experimental studies with this decrease in CO_2 emissions. Less production and usage of cement means less carbon emissions. Consequently, the reuse of these materials in mortar/concrete production seems beneficial.

5.1.3 Assessment of CO_2 emissions in conceptual concrete recycling plant

And now the question is how the usage of RUP instead of cement can affect beneficially the environment in larger scales like the real industry world. The concept with recycling concrete plants is working sustainably until now with the reprocessing and reuse of mainly coarse aggregates and the also the fines. But the separation between the recycled fines and the ultrafines with HAS and the usage of the latter can contribute to a green final product and a more sustainable development with less CO_2 emissions.

For the accomplishment of the investigation for this paragraph, it is necessary the creation of a conceptual recycling plant. Now in industry section, assuming that there is a concrete recycling plant with the usage of HAS and input feed at about 120 ton/h, which concludes to a production of 10 ton/h of recycled ultrafine material, this means 80 ton/day (8 working hours/per day) as final production apart from coarse and fine aggregates. Also, there are control systems like IR sorter and LIBS in the recycling plant to check the contamination of the materials leading to high quality materials. For the separation of the materials some machines like screen, ADR and HAS are helping for the separation of the materials depending on their size. As RUP are defined the materials below 125 microns; these that were used in the 1st and 3rd phase directly of the experimental study of this research. A scheme of a recycling plant with the usage of HAS is the following in Figure 5.1

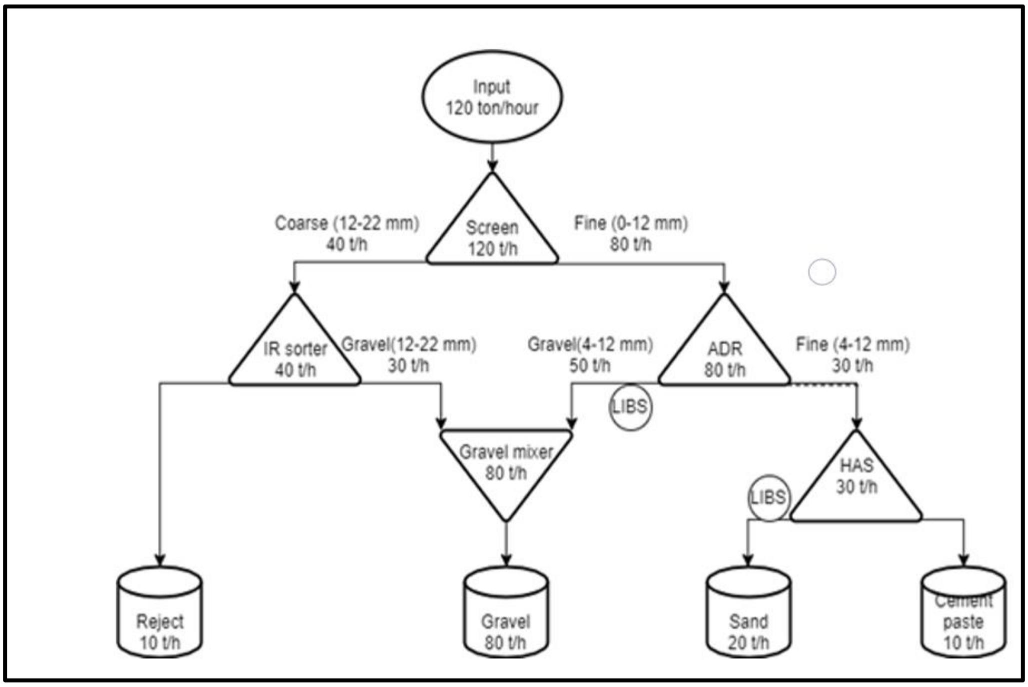

Figure 5.1 A scheme of an innovative conceptual recycling plant with usage of HAS

The approximate CO_2 per litre of diesel fuel is 2.68kg. In the case where HAS is used to further separate cement paste from the fine particles, a typical engine of 16.2L diesel for heating is used for HAS and generates 0.043ton CO_2 per hour (0.35 ton per day). It is obviously a more environmentally friendly idea in contrast to another scenario that not separation of fine and ultrafine particles and making incineration of the total fine aggregate in order to remove the contaminants. In this scenario, where the fine mixture is incinerated onsite to remove the contaminants, assuming 50 L/ton-waste diesel usage, the incinerator would generate (EUROPEAN COMMISSION, 2006) :

50 *30 (fine aggregates) *8 (hours)* 2,68 = 32.2 ton of CO2 per day

The final production of the recycled cement paste is 80 ton/day and it is a hydrated product. This recycled ultrafine material could be used in mortar/concrete production either as hydrated as in the previous experimental study for lower quality product e.g. use in road construction or according to the literature they can be dehydrated with thermal methods in order to increase the quality of the final product for reuse in building materials. The hydrated cement paste can be sold to a cement kiln in purpose of reusing in mortar/concrete manufacture. There will be a useful environmental gain from the substitution of cement with RUP in the concrete/mortars. With 10 ton/h and 80 ton/day production of recycled cement, that they can substitute the cement in mortar/concrete production, RUP can offset:

10*0.9 (factor of CO_2 emission if cement would be used instead) = 9ton CO_2 per hour, or 72ton CO_2 per day.

Furthermore, it is important to calculate the emission during the transportation of the recycled cement paste to the cement clin. Assuming that this concrete recycling plant is constructed in the country of the Netherlands, in the suburbs of Amsterdam, where many industries have this location. Also, there is a cement clin factory in the city Maastricht. In order to transport cement paste to Maastricht, a 210 km journey must be made. A 2009 truck with an engine that complies with Euro 5 and legal requirements could make this journey. This truck due to big distance should have a trailer for long-haul traffic. The total weight of the truck is 60 ton and the payload weight is 40 ton. The daily product of the recycled cement paste is 80 ton/day, this means 2 trips to go to the cement clin with full truck with payload weight and 2 trips to return with empty truck,4 trips in total per day. The full load truck needs 43-53 liters diesel fuel per 100 km, while the empty load truck needs 27-32 liters diesel fuel per 100 km. (Volvo, 2019) As it was referred the distance is 210 km, so with 50 liters on average diesel fuel per 100 km for full load truck and 30 liters for empty load truck, the daily consumption of fuel and emission of CO2 because of the transportation of recycled ultrafine materials will be:

Full: 50+50+5=105*2=210 liters diesel/per day needed *2,68=562.8kg/day CO_2 emission

Empty: 30+30+3=63*2=126 liters diesel/per day needed* 2,68= 337.68kg/day CO_2 emission

In total: 562.8+337.68=900,48kg/day = 0,9 ton/day CO2 emission for transportation

It would generate 0.9 ton /day in total for transportation with trucks which is the most common way of cargo shipping worldwide (Volvo, 2019).

In the Table 5.2, there is a presentation of the CO_2 emissions and the environmental gains with the reuse of the recycled cement paste in contrast to the burning of the fine aggregate in an innovative recycling plant.

Method	CO_2 emissions by HAS (ton /day)	CO_2 emissions by incineration (ton /day)	CO_2 emission by transportation (ton /day)	CO_2 offset (ton /day)	Total CO_2 emission (ton/day)
HAS+ TRUCK	0.35	0	0.900	72	-70.75
Burning	0	32.2	0	0	+32.2

Table 5.2 Total CO_2 emissions with and without the use of HAS system

According to the Table 5.2, there is an environmental gain with the usage of HAS with target to separate recycled fine and ultrafine material below 125 microns. Supposing that using the method of burning through incineration for the fine aggregate the environmental footprint is increased with 32.2 ton /day CO_2 emission for a typical concrete recycling plant that ignoring RUP. This a big quantity of carbon emission that provokes air pollution to the environment. It is obviously not a very environmentally friendly and sustainable solution. In contradiction to this scenario, the use of HAS seems to contribute beneficially the fact of the carbon emissions. Surely, the procedure of mortar/concrete manufacture is a not environmentally friendly industry, because the calcination of the cement is negative for the environment. But the substitution of cement with recycled ultrafine materials until specific rate, it can help the environment with decreasing the CO_2 emission and keeping simultaneously the quality of the mortar/concrete at good level. In this concrete recycling plant, with the use of HAS system-separation of RUP and the transportation with trucks, there is an environmental gain with total CO_2 offset of 70,75 ton/day. This amount can contribute and reduce the total emissions during the concrete manufacture with less participation of cement. Furthermore, it can be referred that this amount equals to the use of recycled ultrafine materials directly as hydrated. According to the literature, the dehydration of the recycled fine grade can improve the quality of the final product of mortar/concrete, but the environmental benefit will be less with burning of ultrafines which leading to more emissions of CO_2. It is important also to note about the following economic analysis of the research that the current price of CO_2 European Emission Allowances is at 25 EUR per ton (EUROPEAN COMMISSION, 2006). Hence, there is a possibility for additional economic benefits from the ecological gain, because European Union pays for CO_2 offset something that it is known as Carbon trading, sometimes called emissions trading, a market-based tool to limit GHG.

In conclusion, there are obviously environmental advantages from the separation and the reuse of the recycled cement. The results from the investigation regarding the experiments and a typical recycling plant seem to encourage the increase of the reuse of recycled ultrafine materials in mortar/concrete production because of their assistance to minimize the environmental footprint. Typical concrete recycling plants like the assumption in this research of Amsterdam could be work at the same level worldwide with the use of HAS system and the transportation of the recycled cement paste to a cement clin. The reuse of the recycled cement seems to lead to the creation of green mortar/concrete and to a more sustainable development regarding the reduction of the environmental pollution. Moreover, a vital parameter for the sustainable development is the section of the economy. Hence, the next step is to combinate these ecological benefits with a new market and profit, something that will be explained in the next paragraphs.

5.2 Economic analysis

The economic approach is an important object for the viability of the recycled products and the wide reuse of them that is combined with the confidence of the customers regarding the final products. Apart from the ecological benefits which were studied in the previous paragraph, it would be important for recycled materials and especially for ultrafine recycled particles to generate economic benefits or being able to compete with other products in the market or create a new market altogether. The target in this part is to answer in the 3rd research question about the expectations for economic benefits from the usage of recycled materials in mortar/concrete industry.

5.2.1 Background on economic perspectives and economic analysis methods

Reusing recycled aggregates has ecological and economic advantages to virgin materials, but are directly affected by some economic parameters, such as (Tam et al., 2018):

- Price and quality are the most significant factors for the decision between recycled and virgin material. It is thought that the concrete products with recycled aggregates can have close to the similar level of quality with the ones of virgin aggregates. But it seems that the customers have not yet a total confidence on recycled materials especially for their use in building constructions. Hence, initially the price of the recycled materials could be somewhat lower than the virgin materials to affect the market demand (M. Head, 2006).

- An obstacle for the market of recycled materials can be the variation of the quality of them. Something that can help is the improvement of the technology and the evolution of C&D processing plants with a target to improve the quality of all recycled products. Many customers such as concrete producers and contractors have concerns regarding the technical feasibility of the recycled materials and they wonder if they meet the high-quality requirements. The high-quality can guarantee the use of recycled materials in the concrete industry and reduction of the usage of virgin materials (Evangelista & Brito, 2014).

- Another problem in order to enhance the presence of the recycled materials in the market is the lack of a well-developed collection and processing facilities/infrastructure. The evolution of the technology can help to improve the collection and processing methods.

- It is important for recycled aggregates and especially recycled ultrafine particles to be in enough to be useful for the construction companies. This means that there is a shortage of recycled materials until now in the market of the construction field. This a very big and considerable concern for the most customers and can affect negative the demand the choice in the market (Y.Kasai, 1998).

- Another issue is the transportation of the recycled materials. The cement factory should be located near to the concrete recycling plant in order to reduce the transportation costs and to enhance the profit (Lauritzen, 1998).

- Some other factors that can affect the recycled aggregate and material market are: taxation in mining activity of virgin aggregate, availability and cost of recycled and virgin aggregate, taxation on landfills and misconception and bias against the performance and reuse of recycled materials (Tam et al., 2018).

To summarize these points, the reuse of recycled aggregate materials in the construction industry is affected mostly by the parameters below according to the Figure 5.2, which depicts the visualization of the most crucial points:

- Variation of price and quality;
- Development of collection and processing facilities;
- Shortage of recycled materials and transportation;
- Taxation of activities for their reuse like mining and landfill.

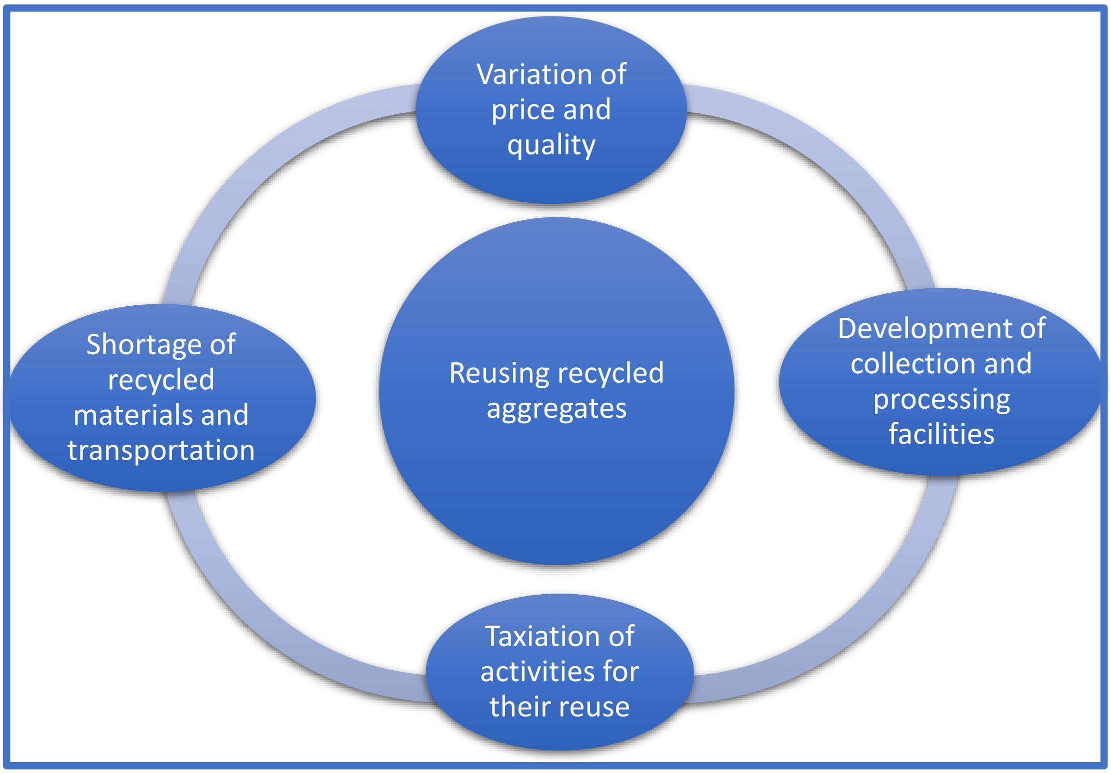

Figure 5.2 The parameters that affect economically the reusing of recycled aggregate

For this thesis, there were three choices regarding the best suited approach for the economic analysis of this research: *Multi-Criteria Analysis, Cash-Flow Analysis (CFA) and Cost-Benefit Analysis (CBA).*

- The first choice was the *Multi-Criteria Analysis*. In this analysis, the benefits and the costs of the business case are weighted in a specific range for example 1-5 points. This approach could help to decide if the case would have a possibility of economically beneficial result, so it gives a general estimation about the effectiveness of the idea. But this approach was declined, because in this business case, there was a need of some numbers to forecast the profitability of the idea and the value of the products.

- The second choice was the *Cash-Flow Analysis (CFA)*. This method seems to be a suitable one. It could lead to the accurate calculation of the profit of such a business case. But obviously there were some problems for its usage, because some parameters here were unknown. For example, the taxes depend on the country of the investment and they are different for each country. Also, it was difficult to approach them for a conceptual recycling plant. The location for this research was the Netherlands. The 2019 Dutch corporate tax rate was 19% of the taxable income up to and including 200,000€, above which the rate was 25%. The lower rate is decreased to 16.5% in 2020. The rates will further decrease to 15% and 21.7% respectively in 2021 (Wagenmakers, 2018). Furthermore, there could be some allowances from the governments like the Dutch for the new environmentally friendly businesses, that it was difficult to be investigated for this business case. For instance, if you are an owner of a company in the Netherlands and you invest in environmentally friendly business assets, you may be eligible for the environmental investment allowance (Netherlands Enterprise Agency, 2020). The deduction could be up to 36% of the capital outlay from taxable profit in addition to the regular depreciation. The deduction includes the following costs:

- Purchase costs;
- Production costs (i.e. the costs you would incur if your company produced the business asset itself);
- Modification costs and/or the cost of purchasing new components;
- The cost of environmental consultancy (only for SMEs).

These and some additional parameters are the reason that it is difficult to estimate the clear profit and the Free-Cash Flow from such a business.

- Free cash flow = sales revenue - (operating costs + taxes) - required investments in operating capital
- Free cash flow = net operating profit after taxes - net investment in operating capital (Watkins, 2012)

❖ The third choice was the *Cost-Benefit Analysis*, known as *CBA*. It is a useful and quick tool-technique that it can be used for non-critical financial decisions, which introduced in 1950s. It is an easy way to weigh up costs and benefits of a research or a project. It involves adding up the benefits of a course of action, and then comparing these with the costs associated with it. The time that is needed for benefits to repay the costs is called payback period and it is a factor of the effectiveness of the CBA. The steps for a typical CBA are shown below (Watkins, 2012):

i. Make a list for all the possible costs and benefits during the lifetime of the project and unexpected costs and/or benefits

ii. Costs include the physical resources needed and the cost of the human effort involved in all phases of a project. It is thought that the costs are easier to be estimated in contrast to revenues.

iii. Assign a monetary value to the benefits. It is difficult to approach the revenues with much accuracy and especially for new products like the recycled ultrafine particles. Simultaneously with the financial benefits, there are often intangible, or soft, benefits that are important outcomes of the project e.g. environmental benefits

iv. Compare the value of the costs to the value of your benefits. It is significant to calculate the payback period in order to reach to the break-even point, the point in time at which the benefits have just repaid the costs. The payback period is estimated by dividing the projected total cost of the project by the projected total revenues: Total cost / total revenue (or benefits) = length of time (payback period).

There is a visualization of these steps of CBA according to the Figure 5.3 below:

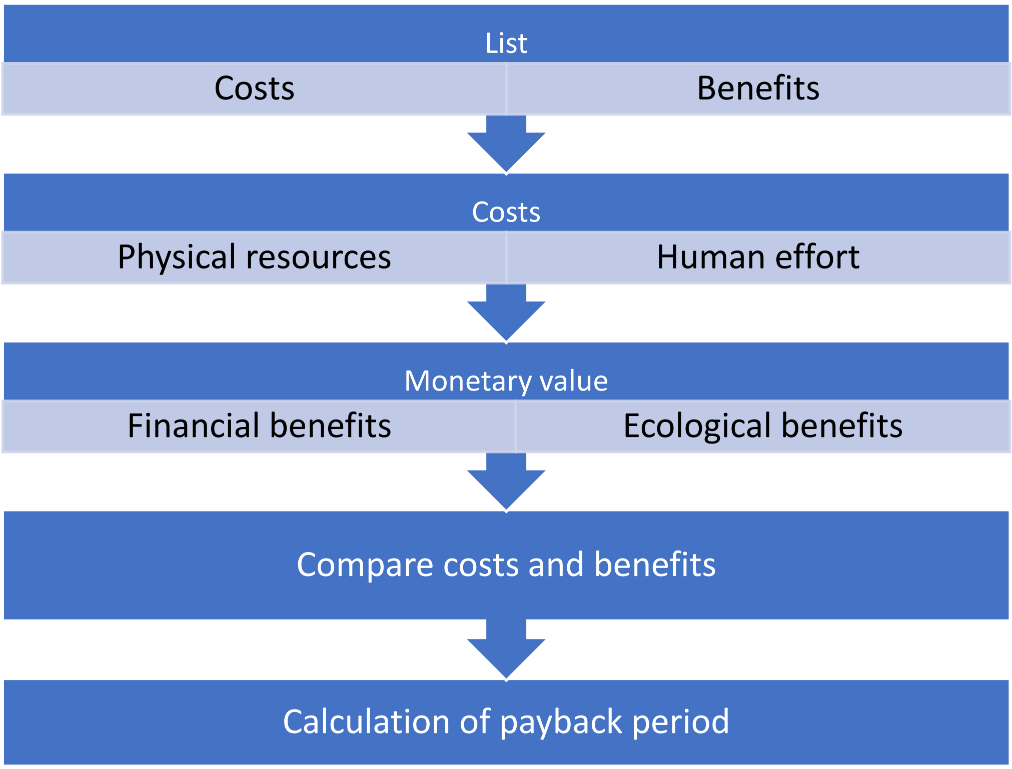

Figure 5.3 The steps for the formulation of CBA

The main drawback of this method is that the calculations regarding the revenues from the benefits associate with a big degree of uncertainty (Watkins, 2012).

In the conclusion, after the presentation of the methods of economic analysis with their advantages and disadvantages, it is important to reveal the best economic approach for the case in this research. The goal is to conduct a general numerical economic approach about the existence of profitability with the separation and the reuse of recycled materials. Hence, a Cost Benefit Analysis combined with calculation of some Cash-Flows seems to be the most appropriate and suitable tool for this case and better approach than the clear Cash-Flow Analysis. So, the conceptual framework that will be used for evaluating these possible economic benefits from this business case is an integration of Cost-Benefit Analysis (CBA) and Cash-Flow Analysis (CFA) into a two-tiered methodology (Harlow, 2018).

5.2.2 Integration of Cost-Benefit and Cash-Flow Analysis in business case evaluation of conceptual recycling plant

It is important for the project of the recycled materials and especially RUP to study the possible revenues from their reuse in the mortar/concrete industry. The integration of CBA and CFA in two levels can be a helpful tool that it will be used in this research in order to prove the viability of this kind business like a recycling plant that is based on the industry of recycled aggregates and especially recycled ultrafine materials. Hence, it is necessary to make a business case in the concrete industry including the use of recycled aggregates and especially recycled ultrafine particles. The focus of this business case is to reveal the economic perspectives of the recycled materials through one example that depicts their usage. This is the target to show the circularity of the recycled ultrafine materials in combination with the external benefits to the society like the ecological ones.

For the accomplishment of this business case, it is obligatory the creation of a conceptual recycling plant. The conceptual recycling plant from the previous section (5.1.3) in the ecological analysis that is depicted in Figure 5.1 in that section will be used for the following economic business case. Assuming that this conceptual recycling plant is located in the suburbs of Amsterdam that processes and produces coarse aggregate-gravel (80ton/h), fine recycled material (20ton/h) and ultrafine recycled material (10ton/h) with the usage of HAS in same amounts of production as in this paragraph. The products will be transfer to a cement manufacturer in Maastricht in this example; the distance is 210 km as it was referred.

Several stages were identified in the formation of this integration of Cost Benefit Analysis and Cash-Flow. The first stage includes the calculation of capital costs for the acquisition of the land, the construction of the recycling plant and the machinery. The second stage has the operating costs for the machinery, the production of the materials, the transportation and the general daily costs. The third part of this evaluation consisted of evaluating the benefits from selling the recycled materials to the cement manufacturer and fourth part of evaluating environmental benefits. Afterwards, it is significant to calculate the payback period of the investment to specify the time period that is needed to make profit from the recycling plant.

In the Figures 5.4 and 5.5, there is the visualization of the costs and the benefits for this business case in details respectively, that reveals all the advantages of the use of recycled ultrafine particles. Furthermore, in the table 5.3 below, there is the CBA and the CFA with comments about the calculation of each cost or benefit and final total calculation of all the costs and benefits with the respective source for each item (Table 5.3). The orange color in this table depicts the capital costs, the yellow color shows the operating costs, the green color depicts the benefits from recycled materials and the purple one reveals the economic benefits through the ecological advantages.

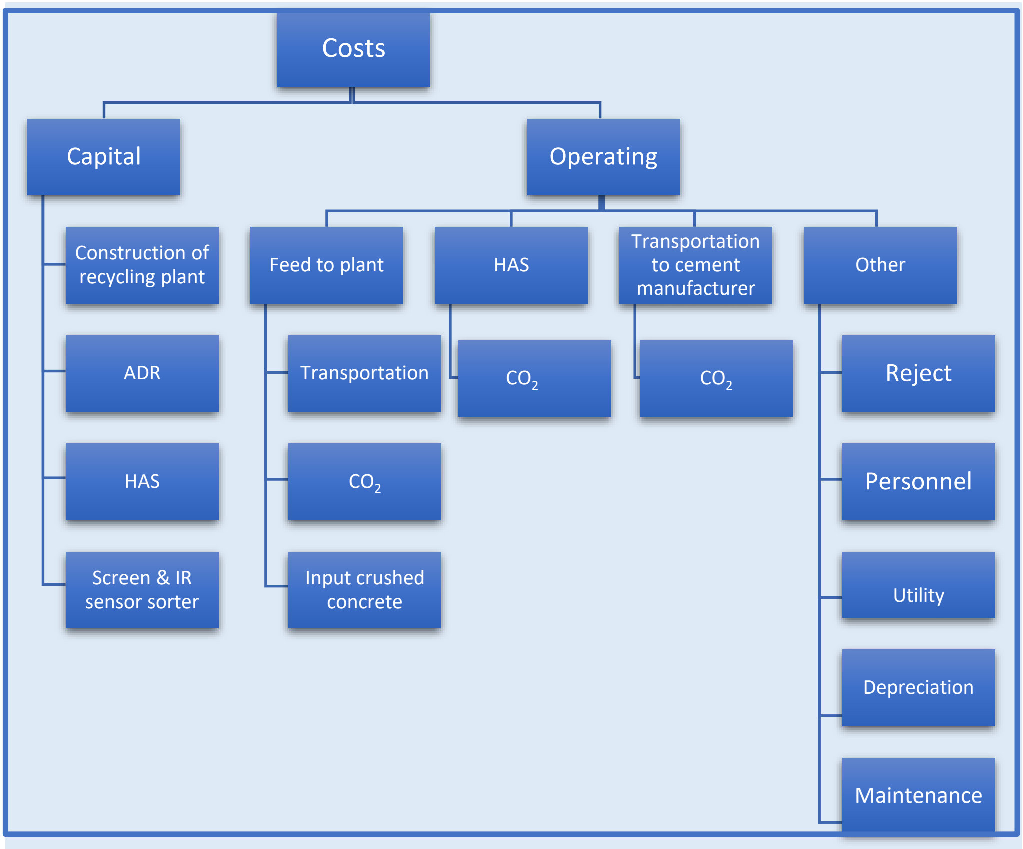

Figure 5.4 The diagram with the costs of the economic analysis

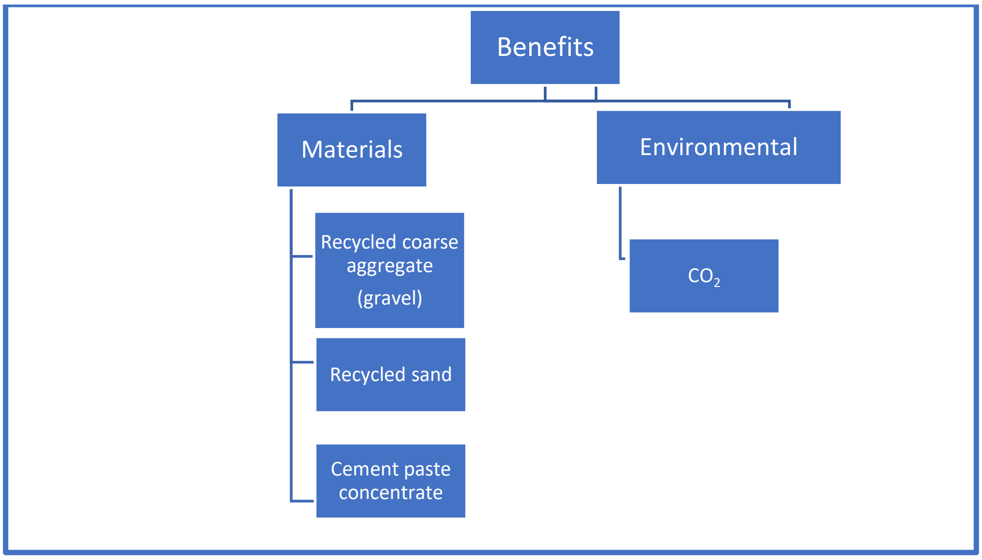

Figure 5.5 The diagram with the benefits of the economic analysis

Equipment/Material /Procedure	Costs €	Benefits €	Comments	Source
1. Capital costs	**2,4M**			
1.1 Construction of recycling plant	1,4M		Includes land acquisition (300 m^2*3500€/m^2= 1.050.000€) groundworks (150.000€) and construction (200.000€)	(Amsterdam, 2020)
1.2 Screen & IR sensor sorter	200K		For the initial purchase only	(Rem, 2016)
1.3 ADR	350K		For the initial purchase only	(Rem, 2016)
1.4 HAS	450K		For the initial purchase only	(Rem, 2016)
2. Operating costs	**11682.16/ day**			
2.1 ADR	960/day		For the daily operation	(Rem, 2016)
2.2 HAS	1200/day		For the daily operation	(Rem, 2016)
2.3 Transport feed to plant	1080 /day		0.75€/km, 30 km with 20t truck, 6 trips, 8 hours	(Trucking, 2020)
2.4 Carbon allowance (input)	19.8/ day		0.0275kg CO2/ton-km, 30 km, 120 t, 25 EUR per ton CO_2 ->0.792 ton	(EUROPEAN COMMISSION, 2006)

2.5 Input crushed concrete	4800/day	5€/ ton hour,120ton/hour	(Rem, 2016)
2.6 Carbon allowance (HAS)	8.75/day	16.2 L/hour diesel 0.35ton CO_2*25	(EUROPEAN COMMISSION, 2006)
2.7 Transport recycled cement to Maastricht	630/day	0,75€/km 4 trips, 210km	(Volvo, 2019)
2.8 Carbon allowance **(truck to Maastricht)**	22.5/day	0.9 CO_2 daily production	(EUROPEAN COMMISSION,2006)
2.9 Reject (landfill)	400/day	10 ton per hour, 5€ per ton	(EUROPEAN COMMISSION,2006)
2.10 Personnel	1600/day	wage to €25/h, 8 personnel	Personal suggestion
2.11 Utility	460/day	23 cent per KWh, 250 kW power/per hour 0,2*250*=460/day	(news, 2019)
2.12 Depreciation	311,11/day	Depreciation over 18 years of operation 1.4M/18/250	Personal estimation
2.13 Maintenance	100/day	Keep this money every day for maintenance of the machinery when it is necessary	Personal suggestion

3. Benefits from recycled materials	**14080/day**		
3.1 Recycled coarse aggregate (gravel)	9600/day	15€/ton	(Moreton Bay Recycling, 2019)
3.2 Recycled sand	2880/day	18€/ton	(© Ashville Aggregates LTD, 2020)
3.3 Cement paste concentrate	1600/day	20€/ton	Landmark product of the recycling plant Estimated price
4. Environmental benefits	**1768.75/ day**		
4.1 CO2 offset allowance from recycled ultrafine particles	1768.75/ day	70.75ton CO_2/day*25	Paragraph 5.1
Total capital costs = 2.4M (one time) **Total operating costs =11682.16€** **Total Benefits = 14080+1768.75=15848.75€ per day operation for 18 years of this recycling plant**			

Table 5.3 Parameters calculation of CBA and CFA

The target of this recycling plant in this business case is to be operated for at least 18 years, so everything is calculated daily for this time period. According to the Table 5.3, the capital costs were identified for the construction of the recycling plant(1,4M) and the purchase of the machinery like screen and IR sensor sorter (200K), ADR (350K) and HAS (450K) reaching at 2.4 Million € as initial investment. It is paid only one time as capital cost. In the following paragraph, there is an analysis for the final amount of 2.4 Million €.

Construction of recycling plant: It includes land acquisition in the suburbs of Amsterdam, groundworks and construction of the building. For the land acquisition in this area, there is a need to pay about 3500€/m^2. For a regular recycling plant at the size of 300m^2, a capital of 1.050.000€ is needed. For the groundworks, an amount of about 150K € seems good enough whereas 200K € for the construction of the building could be feasible (Amsterdam, 2020).

Screen & IR sensor sorter: Screen is a visual operational system using a high-speed camera and a special conductivity sensor guaranteeing the identification of a variety of materials. The main goal of the usage of IR sensor sorter is to separate mixed recycled aggregates with a substantially higher technical and environmental quality from reject, that means from lower soluble sulphate contents and organic matter contents. For their purchase, the estimation is about 200K € (Rem, 2016).

ADR: ADR technology is a mechanical system of sorting and classifying wet CDW particles according to their particle size. The capital cost for its purchase can reach at 350 K € (Rem, 2016).

HAS: The HAS technology is created to further expose the fine fraction aggregates (0-4mm) into a hot gas, targeting to remove the associated moisture, destroy undesirable CDW contaminants mainly wood and plastics, by burning them out and to produce clean sand and hardened cement paste product leading to separation between fine and ultrafine particles. It is a relatively expensive machine with a capital cost at about 450 K € (Rem, 2016).

Regarding the operating costs, they include many significant parameters. The costs were calculated with the factor that the working hours per day are, so multiplying the cost of each parameter per hour with 8 hours or with kilometres for transportation. The total operating costs for this recycling plant are 10442.16 € per day. More detailed:

Machinery: For the ADR the cost is 120 € per hour, so the daily is 960 €, whereas for the HAS 150€ per hour and 1200€ per day respectively (Rem, 2016).

Transport the feed to the plant: The most possible solution is to use trucks to transport the feed from different sources into the concrete recycling plant. The average for the trucks is 0.75 € per kilometer. It is needed 120 ton /hour as input. If the source is in Amsterdam city (many demolished buildings), so a radius of 15 km to go and 15 km to come back; every truck is used for 30 km per hour. They are needed 6 trucks of 20t, leading to a totally usage of 180 km per hour, multiplying with 8 hours and the factor 0,75, gives 1080€ per day (Trucking, 2020).

Carbon allowance (input): During the transportation of the feed an input in the plant, there is CO_2 emission from the trucks that used. From the ecological analysis, it is known that the emission is estimated 0.0275kg CO_2/ton-km. So, for 30 kilometers and 120 tons, it is produced 0.792 ton of CO_2 per day. The European Union charges 25€ per ton CO_2 leading to a daily cost of 19.8 € (EUROPEAN COMMISSION, 2006).

Input crushed concrete: It is obligatory to pay in order to buy the crushed concrete as input. A price of 5 € per ton per hour, it seems to be a feasible one for this kind of materials. It is needed 120 ton per hour and 8 hours per day, so it is concluded to a cost of 4800 € per day (Rem, 2016).

Carbon allowance for HAS: According to the ecological part, HAS needs diesel as a fuel for its action, leading to a production of CO_2 with 25 € per ton CO_2 as a charge. Hence, with the usage of 16.2 L diesel per hour, the total daily production of CO2 is 0.35 ton, provoking a cost of 8.75€ per day (EUROPEAN COMMISSION, 2006).

Transportation of recycled cement: The recycled cement after the process should be transported to the cement manufacturer to Maastricht. The distance is 210km. The daily production of recycled cement according to the ecological analysis is 80 ton. The cost for the trucks is 0.75 €/km. The trips are 4 with full and empty trucks, hence the daily costs for the transportation of recycled cement is 630€ (Volvo, 2019).

Carbon allowance of recycled cement transportation: During the transfer of the recycled cement from the recycling plant to the cement manufacturer, according to the paragraph 5.1.2, there is a production of 0.9 ton of CO_2 per day. That means with the charge of 25 € per ton CO_2, that the costs reach at 22.5€ per day (EUROPEAN COMMISSION,2006).

Reject (landfill): According to the Figure 5.1, there is a rejected material from the plant as contaminants. Its production is 10 ton per hour that means 80 ton per day. With 5 € per ton for landfill, the daily cost for landfill is about 400€ (EUROPEAN COMMISSION,2006).

Personnel: For the operation of the plant is obligatory to have people to conduct all the procedures. 8 workers seem to be enough for this size of plant with a wage 25 € per hour that means 200 € per hour and 1600€ as a total daily cost.

Utility: Energy is necessary for the operation of the recycling plant. It is possible through the recycling of waste to create electrical power. But the target of this plant is to support the beneficiary reuse of the recycled ultrafine particles. Regarding, the electricity the kwh costs 20 cents. An electrical power of 250 kwh is enough, leading to demand of 2000 kwh per day with a total daily cost of 400 € (news, 2019).

Depreciation: It is thought that this investment will undergo depreciation in time period of 18 years with a constant decrease. The initial capital was 1.4M €, so this amount will be divided by 18 years and 250 working days, leading to a daily depreciation of approximately 311 €.

Maintenance: According to a personal estimation for this recycling plant and business case, there will be some extra costs for maintenance of the machines and the general plant during these 18 years. An amount of 100 € per day to save could help for the solution of the problems in the future,

Regarding the benefits and the revenues that will produce from selling the materials to a concrete producer and the cement manufacturer. The daily benefits from the recycled products are 15848.75€. The most expensive material is thought to be recycled cement paste because it is a special material that can substitute cement in concrete production. The benefits were calculated:

Recycled coarse aggregate (gravel): It is the product with the biggest production from the recycling plant and a product that it is already used in many constructions. It has the lowest price among the recycled materials, but it offers a wide benefit due to its large production. Making a research in the existing market, the recycled gravel costs about 19.80$/ton, so 16,24€/ton (Moreton Bay Recycling, 2019). With a defined normal competitive price of 15 €/ton and a production of 80 ton per hour, the daily benefit in this recycling plant from recycled coarse aggregate can be 9200 €.

Recycled sand: It is the fine recycled material below 4mm which is produced after the usage of HAS. An important parameter is that natural sand gets limited in some places worldwide, so the price of recycled sand tends to be increased in the market. Making an investigation in the existing market, the recycled sand costs about 18.50£/ton, so 20,57€/ton (© Ashville Aggregates LTD, 2020). Hence, an initial price of 18€ per ton seems good and competitive for the recycling sand from this recycling plant. With production of the recycling plant at 20 ton per hour, the final daily benefit from recycled fine material is 2880€.

Recycled cement paste: This material is the target and the landmark product of this recycling plant, and it can be sold to a cement manufacturer after the separation from fine particles with the usage of HAS. It is the most processed material. It has the capability to substitute the cement in the concrete production with simultaneously big ecological benefits. Hence, its price will be somewhat higher than this of the recycled sand. A price of 20€ per ton seems to be feasible with a production of 10 ton per hour leading to 1600€ benefit from the use of recycled ultrafine particles in 8 hours each day.

Finally, the most important target of this business case is to have economic benefit from the environmentally friendly behavior of the reuse of recycled cement paste. According to the paragraph 5.1.3, from the substitution of cement with recycled ultrafine particles can be saved approximately 70.75 ton of CO_2 emissions as an offset. With the guideline from European Union about an allowance of 25 € per ton, leading to a daily benefit 1768.75€ from the reuse of the recycle cement and its ecological benefits.

Other significant parameters for this conceptual recycling plant are the calculation of Net Present Value (NPV) and the estimation of the potential payback period for this business case. It is assumed in the scenario of this plant that the discount rate equals to 10% (i =10%), something that it is common in the real business cases and in Cash-Flow analysis; usually within 6-12% (Majaski, 2020). The discount rate makes it possible to estimate how much of the project's future cash flows would be worth in the present. Many companies calculate their weighted average cost of capital (WACC) and use it as their discount rate when budgeting for a new project (Majaski, 2020). This conceptual recycling plant was planned with many parameters estimated with assumptions and the lack of taxes calculation.

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment or project (Mansa, 2020). It is assumed that an investment with a positive NPV will be profitable, and an investment with a negative NPV will result in a net loss. This concept is the basis for the Net Present Value Rule, which defines that only investments with positive NPV values should be considered (Mansa, 2020).

NPV equals (Mansa, 2020):

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \quad (1)$$

where:

Rt=Net cash inflow-outflows during a single period *t;*

i=Discount rate or return that could be earned in alternative investments;

t=Number of timer periods.

The conceptual recycling plant is planned for 18 years of operation. Also, it is thought that the working days are 250 per year (104 days of weekend per year plus 10-11 days off; 365-115 days). Hence, some calculations can be done:

t= 0,1,2,3….18 years

i=10% or 0,1

Rt: For year 0, it is defined as the investments cost:- 2.400.000€

For years 1-18, it will be calculated as the annual net cash inflows-outflows in 250 working days per year.

15848.75-11682.16=4166.59*250=1.041.647,50€ per year operation

Rt = 1.041.647,50€ for timer period 1,2,3….18

In the following Table 5.4, there is a calculation for the Net present value (NPV) for the previous business case with the Cash Flow Stream Details for 18 years of operation for this conceptual recycling plant. The NPV factor is a crucial than can lead to conclusion about the potential profitability of this project.

Cash Flow Stream Detail		
Period	***Cash Flow €***	***Present Value €***
0	-2,400,000.00	-2,400,000.00
1	1,041,647.50	946,952.27
2	1,041,647.50	860,865.70
3	1,041,647.50	782,605.18
4	1,041,647.50	711,459.26
5	1,041,647.50	646,781.14
6	1,041,647.50	587,982.86
7	1,041,647.50	534,529.87
8	1,041,647.50	485,936.25
9	1,041,647.50	441,760.22
10	1,041,647.50	401,600.20
11	1,041,647.50	365,091.09
12	1,041,647.50	331,900.99
13	1,041,647.50	301,728.18
14	1,041,647.50	274,298.34
15	1,041,647.50	249,362.13
16	1,041,647.50	226,692.85
17	1,041,647.50	206,084.41
18	1,041,647.50	187,349.46
	Total: **NPV=5,955,631.00€**	

Table 5.4 The calculation of the NPV for this business case

The NPV was estimated 5.955.631 € in 18 years. This means that the value is positive and higher than zero. Consequently, NVP= 5.955.631 € >0 and this result dictates that this conceptual recycling plant could be obviously profitable with the Net Present Value Rule.

The next step is the estimation of the payback period of the investment of this business case with the assistance of the previous NPV calculation. The payback period is estimated by making an equation with the total costs dependent on time and the total benefits dependent on time (MIND_TOOLS_TEAM, 2020); (Watkins, 2012). The day that the benefits equal the costs, that defines the time of return of the initial investment. For this calculation, it is thought that the working days are 250 per year as in the calculation of NPV. The following Table 5.5 shows the estimation of the payback period through the NPV calculation, with time that the gains from the operation of the plant equals the initial investment.

Payback Period

Period	*Cash Flow €*	*Present Value €*
0	-2,400,000.00	-2,400,000.00
1	1,041,647.50	946,952.27
2	1,041,647.50	860,865.70
3	1,041,647.50	782,605.18
	Total:	**NPV=190,423.20**

About 33 months

(<36 months =3years)

without taxation calculation

(782/12 months =65 per month *3 =195 about 190)

36-3=33 months

Table 5.5 The payback period of this business case

After 3 years of conceptual recycling plant operation in this scenario, the NPV is estimated to be 190.423 € >0 at discount rate i=10%, this means that the initial investment was covered by the gains and from the project is profitable. The day that the benefits equal the investment costs is some months before the completion of 3 years, hence the payback period is estimated to be about 33 months without estimation of taxations. This a general approach without the accurate taxes or some allowances from the government for environmentally friendly businesses.

Summarizing in the Table 5.6, it is depicted the total information, characteristics and details from the results regarding the conceptual recycling plant that was used in this research to evaluate the possible ecological and economic advantages from the reuse of recycled materials such as RUP and recycling sand in the mortar/concrete production.

Conceptual recycling plant	
Characteristics	**Details**
Location	Suburbs of Amsterdam (areas with price 3500€/ m^2)
Size	300 m^2
Time Duration of Operation	8 hours/day operation 250 working days 18 years operation
Personnel	8 personnel (wage to €25/h)
Input	120 ton/h
Output	Reject 10 ton/h Recycled gravel 80 ton/h Recycled sand 20 ton/h Recycled cement paste (RUP) 10 ton/h
Transportation to	Cement clin in Maastricht (210km)
Vehicles for Transportation	2009 truck with an engine-Euro 5 and a trailer for long-haul traffic. The total weight of the truck is 60 ton and the payload weight is 40 ton. 2 trips (2 full and 2 empty for RUP)

Ecological benefits	Reduction of CO_2 emissions (-70.75 ton/day) Less air pollution Less waste for landfill and incineration
Business Case	Integration of Cost-Benefit and Cash-Flow Analysis
Costs	Capital costs 2,4M € (one time) Operating costs 11682.16 €/working day for 18 years
Benefits	Recycled materials 14080€/working day for 18 years Environmental benefits 1768.75€/working day for 18 years
NPV	5.955.631 € >0 profitable At discount rate i=10%
Payback Period	About 33 months without taxation and allowances

Table 5.6 The total characteristics and details of the conceptual recycling plant

5.3 Investigation for potential sustainable and green development

The next step in the assessment of the ecological and economic parameters for the usage of RUP and other recycled materials in the mortar/concrete production is to investigate the potential sustainable and green development due to their reuse. In the introduction part of this chapter, there are some definitions about these terms and the circular economy. These definitions will be the theoretical background combined with the results from the ecological and economic analysis of the conceptual recycling plant before will help to the evaluation of the sustainability and the green potential of the object of this MSc thesis.

Regarding the sustainable development from the reuse of recycled materials and especially RUP, it will take only the environmental and economic parameters into consideration for this research. The results from ecological analysis revealed that the substitution of cement with RUP in mortar/concrete production can reduce the GHG and especially CO_2 in very good level. The simulation numbers seem very encouraging for this innovative mortar. The air pollution will be decreased significantly. Also, less space will be used for landfill of the waste. Furthermore, the reuse of the recycled materials like RUP or recycled will help to less consumption of natural resources and their conservation also for the next generations. Furthermore, the results from the economic analysis show that a conceptual recycling plant that focusing on reuse of RUP and other recycled materials can be a profitable one in the present and future with a feasible payback period for such business. It seems to have great perspectives for circular economy, because circular economy targets to create a closed-loop system with less waste, reuse of materials, less consumption of natural resources and less carbon emissions. The reuse of RUP and other recycled materials in mortars can help to the accomplishment of this goal. Hence, this new mortar or concrete can be characterized as more sustainable than the original ones leading to a potential sustainable development.

Moreover, the green development is another important parameter for the reuse of RUP in mortars. The green development includes three categories: environmental responsiveness, resource efficiency and cultural sensitivity. The use of RUP and other recycled materials like recycled sand corresponds to the resource efficiency parameter. The reuse of recycled materials instead of natural resources can contribute to the maintenance of energy and the conservation of the environment. Especially, the use of RUP instead of limestone (for cement production) and recycled sand instead of natural sand can save many of the natural resources. In addition to these advantages, the decrease of CO_2 emissions can help to the reduction of damage to the ecosystem helping to the environmental responsiveness. Regarding the cultural sensitivity, the reuse of recycled materials in concrete production can contribute to increase the reliability of customers regarding these products. All these data conclude to the argument that the usage of RUP and other recycled materials can contribute to the green development in the mortar/concrete industry.

5.4 Conclusion for ecological and economic analysis

In this chapter, the ecological and economic impacts from the possible utilization of recycled ultrafine particles and other recycled materials like recycled sand were investigated. A conceptual recycling plant was used for this study. The results seem to be encouraging for mortar/concrete industry. Hence, there is a possibility for environmental benefits and a new market for this recycled material.

Through this project, some useful points regarding the ecological and economic attributes were revealed. The most important keys points are presented below:

- Regarding the ecological analysis, the most important point from the substitution of cement with recycled ultrafine particles in concrete manufacture is the reduction of CO_2 emissions and Greenhouse Gases. Until now, the calcination of limestone to produce cement contributes to the emission of carbon dioxide. But the usage of recycled cement paste can reduce this bad consequence. In the example, that it was used in this paragraph to show the ecological benefits of RUP, in a conceptual recycling plant, which send its recycled ultrafine particles to a cement manufacturer, it was revealed that 70,75 ton CO_2/day could be saved from the final usage of RUP in contrast to the traditional method of burning this small material which has negative daily offset of carbon dioxide to the environment with 32,2 ton CO_2/day.

- The conclusion from the economic analysis is that the usage of recycled materials and especially RUP could lead to economic benefits through the European Union norms, giving motivation to the construction of innovative recycling plant with the corresponding technology facilities and RUP as targeted materials. The recycled cement paste is a new material for usage in concrete production that can affect the current economic market or create a new market. The conceptual recycling plant of $300m^2$ in the suburbs of Amsterdam like in the example in this paragraph with recycled ultrafine particles as targeted products and 18 years as a forecast of operation has perspectives to be profitable. According to the economic analysis in this paragraph, the capital costs for this kind of investment are about 2,4€ million (paid one time), the operating costs are 11682.16€ per day and the total daily economic benefits from recycled materials are 15848.75€. The NPV is positive 5.955.631 € >0. This could lead to a great payback period of the investment of about 33 months without the calculation of the taxation inside and with discount rate at 10%.

- The reuse of the recycled cement paste with substitution of cement in the concrete/mortar production can lead to many ecological and economic benefits in the present and in the future, as the physical resources get decreased. The use of recycled materials can save energy and protect the natural environment. There is great perspective for circular economy through the usage of these recycle materials. These ecological and economic benefits can contribute to a potential sustainable and green development in mortar/concrete industry.

Chapter 6

Conclusion and Recommendations

Based on the research conducted some useful conclusions can be drawn which will be elaborated in this chapter. Next to these conclusions, an answer will be given to the research questions raised during this research leading to the investigation of the main objective. Also, this chapter has the purpose to give recommendations for further research. This research has tried to explain the essence for the need of a correct sustainable approach and formulated a framework to achieve the sustainable approach of the use of recycled ultrafine particles. However, this research has some limitations mainly due to the outbreak of coronavirus and the fact that all experiments couldn't be performed fully according to the planning. These aspects will be discussed in this chapter along with recommendations.

6.1 Conclusions

The structural elaboration of this research study has formed the basis and details for answering the research questions of this MSc thesis that can lead to the potential achievement of the research objective. The main objective of this research was:

<u>Objective:</u> " *to investigate if the new mortar with recycled ultrafine particles can substitute the reference mortar made of virgin materials and to investigate the possible accompanying ecological and economic benefits.*"

To investigate the objective of the MSc thesis, it was important to test and answer step by step the three research questions of the research and reach to some conclusions according to their findings. The three research questions were:

<u>1st research question:</u>

Is this new mortar feasible?

<u>2nd research question:</u>

Are there any ecological advantages from the usage of this new mortar?

<u>3rd research question:</u>

What are the expectations for possible economic benefits from the reuse of recycled ultrafine particles and recycled sand in mortar/concrete industry?

6.1.1 Assessment of the 1st research question

The 1st research question has as a target to reveal the technical feasibility of this new mortar with 5,10 and 15 % replacement of cement with recycled cement paste respectively. To prove the technical feasibility of the recycled ultrafine particles, three different experiments were conducted during this research for assessment of the impact of the RUP, the impact of RUP particle size and the impact of recycled sand in the mortar/concrete production:

- *1st experiment:* Assessment of the impact of using recycled ultrafine particles as cement replacement in a new mortar mix

The results indicate that RUP below 125 microns can replace at satisfactory level the cement in the new mortar mix. Especially for mixture with 5 an 10%, the flexural strength measurements were better than these of the reference sample, improving the resistance to deformation under bending and the elasticity of the mortars. Also, the performance of mortar with 5% replacement regarding the compressive is pleasant. The mortars with 10 and 15% of replacement with RUP show a notable reduction. The higher the level of substitution, the low relative compressive strength of mortar is. For a given substitution level, the relative compressive strengths are higher at 1 and 7 days than in 14 days. This can be explained by the effect of acceleration of cement hydration and the increase of hydraulic reactivity of cement due to presence of RUP and their higher specific area (Mahieux, 2020). Moreover, the recycled ultrafine materials have some other different features in contrast to the natural ones like the cement particles and these characteristics can be possible reasons for this loss of mechanical performance in compressive strengths of new mortars. RUP below 125 microns have higher water absorption than natural aggregates, so they absorb more water (Zhao et al., 2015). Furthermore, the compressive strength can be affected by the quality and the origin of RUP (Evangelista & Brito, 2014). Sometimes, it is possible RUP from different sources to have alternative mineralogical composition e.g. different percentage of $CaCO_3$ and hence different cement content. Also, the contamination of the RUP can differ after processing due to residues from reinforcing steel, admixtures used in the old concrete and chemical contamination (e.g., deicing salts, sea salts, oils, etc.) (Evangelista & Brito, 2014). In general overview, the replacement with RUP below 125 microns has satisfactory results regarding the flexural strengths and encouraging results for the compressive strengths despite some problems.

- *2nd experiment:* Evaluation of the impact of the recycled ultrafine particle size on the strength of mortar

Another interesting thing for investigation was the impact of RUP particle size in mortar/concrete mixtures. The results show that the milled RUP can improve the mechanical properties of the mortars. The smaller recycled ultrafine particles are constantly more efficient in flexural strengths than the bigger ones. For compressive strengths, the mortars with 10% and 15% replacement with RUP below 45 microns have better results in contrast to the corresponding with RUP below 125 microns. One important reason is the filler effect in mortar/concrete production. Finely ground mineral powders are known to accelerate cement hydration rates. This “filler effect” has been attributed to the effects of dilution (w/c increase) when the cement content is reduced or to the provision of additional surface area by fine powders. The latter contribution (i.e., surface area increase-high surface area) is speculated to provide additional sites for the nucleation of the hydration products, which accelerates reactions making these smaller particles more efficient (Rates, 2013). Moreover, this filler effect can complete the particles arrangement of cement and thus improve its packing density leading to more compactness of mortar/concrete (Mahieux, 2020). Also, the addition of finer parts of RUP decreases the interparticle distance, leading to an increase to the shear between the particles especially during mixing and therefore it raises the dissolved ions into the solution (Mahieux, 2020). These points conclude to the fact that the mortars containing milled RUP are more compact than these with bigger RUP leading to better mechanical properties.

- *3rd experiment:* Assessment of the formulation of a new mortar recipe that incorporates recycled sand and recycled ultrafine particles

The most complicated experiment was the 3rd, in which the total replacement (100%) of natural sand with recycled sand is evaluated combined with the presence of RUP in some mixtures. The combination of 100% recycled sand with RUP creates very high water absorptivity. The results for this specific recipe seem to be discouraging regarding these mechanical properties. The flexural and the compressive strength of mortars also decrease as the replacement percentage of RUP increases. There are several factors that can be indicated for the poor performance of recycled sand particles. RS can create problems to the mechanical properties of mortars due to the higher water absorption and the adherent cement paste content. Also, this presence of adherent cement paste can lead to higher porosity and water absorption (Zhao et al., 2015). Another factor can be the origin of the RS used. The fine recycled particles that produced from crushed concrete or directly from construction and demolition waste (CDW) have distinct characteristics that affect the mortar/concrete made with them (Evangelista & Brito, 2014). The particle density and loose bulk density of RS particles are lower than those of FNA, because the fine recycled grade can contain mortar and residues from other non-stone contaminants such as brick, gypsum or wood leading to high water absorption (Evangelista & Brito, 2014). The decreased loose bulk density demonstrates the higher degree of angularity of the RS particles in contrast to natural ones. The sphericity also varied more confirming the previous statement about the shape (Evangelista & Brito, 2014). Hence, the 100% substitution of natural sand was very optimistic; the amount of recycled sand should be less for example 50% recycled sand and 50% natural sand. Also, the right amount of extra water compensation in mortar/concrete during the mixing procedure has vital importance. These observations can help to improve the impact of recycled sand in the mortar/concrete mixtures with better results for mechanical properties.

In conclusion, regarding the 1st research question and the technical feasibility of the new mortars with recycled cement paste instead of cement at 5,10 and 15% replacement ratios, the usage of RUP has satisfactory results for the mechanical properties of the mortars; especially for flexural strength and the milled smaller RUP increase the effectiveness regarding the flexural and compressive strengths. The values of slumps and consequently the fresh state workability are excellent for all the mixtures in the experiments. The mortars with recycled sand seem not so efficient, but the right amount of partial replacement with RS and the appropriate quantity of extra water compensation can improve the strengths and the properties of the new mixtures. Obviously, the evolution of the technology in the next years can increase the advantages from the reuse of recycled materials like RUP and RS in mortar/concrete production and simultaneously reduce the drawbacks. For the present, the presence of recycled cement paste in mortars is beneficial and technically feasible.

6.1.2 Assessment of the 2nd research question

The 2nd research question has as a goal to reveal the possible ecological advantages from usage of this new mortar with recycled cement paste. For this investigation, an ecological analysis was conducted. This ecological analysis included in the first part a simulation in the lab experiments and in the second part a simulation in a conceptual recycling plant. The results are pleasant for the both cases regarding the GHG emissions and especially CO_2. Initially, in the lab experiments, 5 % substitution with RUP instead of cement particles leads to 5,1% reduction of CO_2 emissions, 10% substitution with RUP leads to 10,2% reduction of CO_2 emissions and 15 % substitution with RUP leads to 14,8% reduction of CO_2 emissions. Moreover, for the simulation of a conceptual recycling plant, the reuse of RUP in the mortar/concrete industry can lead to significant reduction of CO_2 and less air pollution. Especially for the scenario in this MSc thesis, there is a potential environmental gain with total CO_2 positive offset of 70,75 ton/day from this conceptual recycling plant. Up-to-day, the calcination of limestone to produce cement contributes to the emission of carbon dioxide. But the usage of recycled cement paste can reduce this bad consequence. Other advantages from the wide use of RUP instead of cement in cement/concrete production are less production of waste, less landfill and conservation of natural resources. Hence, in conclusion, there are the perspectives for ecological advantages from the usage of this new mortar with RUP.

6.1.3 Assessment of the 3rd research question

The 3rd research question includes the investigation for the potential economic benefits from the reuse of the recycled materials and especially RUP in mortar/concrete industry. For the accomplishment of this research question, it was necessary the hypothesis of the same conceptual recycling plant like in the 2nd research question. For this business case, an integration of Cost-Benefit Analysis with Cash-Flows was conducted. According to this economic analysis, there are benefits from the creation of market for RUP, recycled sand and coarse aggregate like gravel and their demand as well as from the compensation by the European Union due to the reduction in CO_2 emissions in this innovative conceptual recycling plant. The results revealed that the NPV was 5.955.631€ >0 for forecast of 18 year-operation. This can lead to a great payback period of the investment of about 33 months without the calculation of the taxation inside and with the conceptual discount rate at 10%. It has great perspectives for circular economy, because circular economy targets to create a closed-loop system with less waste, reuse of materials, less consumption of natural resources and less carbon emissions. It seems that the reuse of recycled materials like RUP in mortar/concrete industry can fulfill the expectations about economic benefits from them and encourage these investments.

Another important point from the analysis of 2nd and 3rd question is that the usage of RUP and other recycled materials in mortar/concrete production can potentially contribute to more sustainable and green development. Regarding the sustainable development, only the environmental and the economic parameters were investigated. Environmentally, the usage of RUP in mortars can lead to reduction of CO_2 and less air pollution, less used space for landfill and conservation of natural resources. Economically, their usage can create a profitable recycling plant in the present and future with a feasible payback period for such business. Also, the reuse of recycled materials creates opportunities for circular economy making a closed-loop system with less waste, reuse of materials, less consumption of natural resources and less carbon emissions. Regarding the green development, the reuse of recycled materials and RUP was evaluated by the parameters of environmental responsiveness and resource efficiency. The reduction of CO_2 emissions can help to the reduction of damage to the ecosystem helping to the environmental responsiveness. Also, the reuse of recycled materials instead of natural resources can contribute to the maintenance of energy and to the conservation of the environment and some virgin materials helping to resource efficiency parameter. The above findings conclude to the argument that the usage of RUP and other recycled materials can lead to sustainable and green development in the mortar/concrete industry.

In conclusion, although some technical drawbacks, the usage of RUP in new mortars instead of cement seems very satisfactory, and especially milled smaller RUP have beneficial effect to the mechanical properties of the mortar. Recycled sand is a material that needs more investigation about the appropriate parameters. The reuse of recycled materials and especially RUP contribute to some ecological advantages regarding the CO_2 emissions. Also, there are possibilities for economic benefits for recycling plants with RUP as targeted material in products leading to the potential model of circular economy. Finally, RUP and other recycled materials can be the basis for sustainable and green development. Hence, recycled cement paste has as an impact the development of sustainable mortar in this industry.

In the Figure 6.1 below, it is depicted the whole framework of the total MSc thesis. The route from the three different research questions and the assessment of them, leading to the positive evaluation and evidence of the main objective of the research.

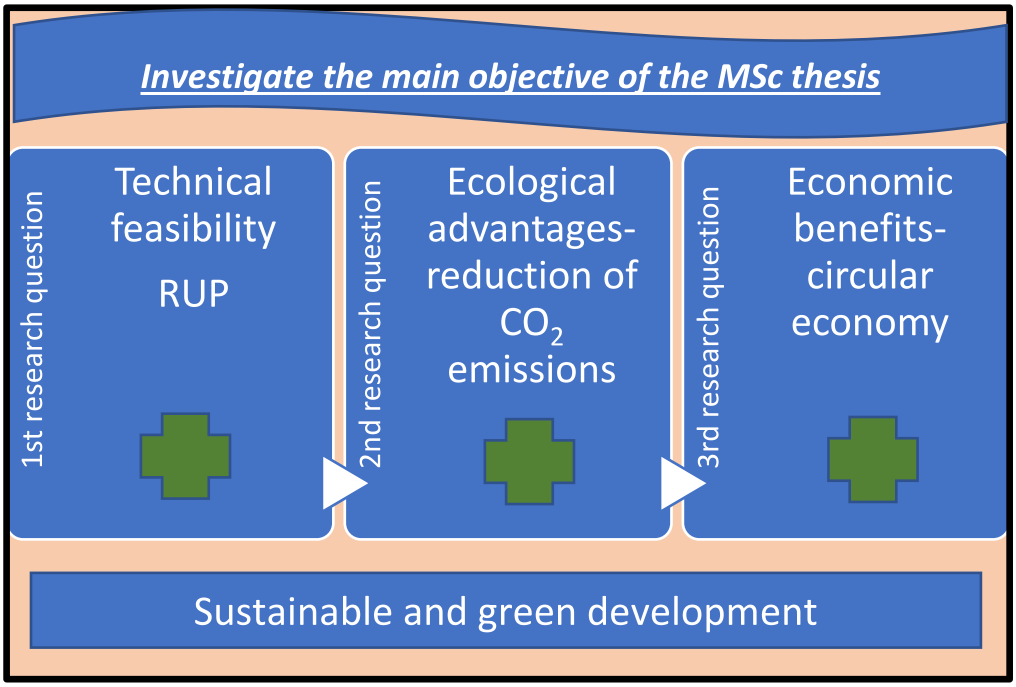

Figure 6.1 Investigate the main objective of the MSc thesis

6.2 Recommendations

The last part of this MSc thesis has as a goal to give recommendations for further research in the future regarding recycled ultrafine particles and recycled sand and their reuse in the field of mortar/concrete production. This research targeted to prove the feasibility and benefits from the use of recycled cement paste and their ecological and economic impacts. Hence, a specific framework was formulated to achieve this sustainable approach. However, conducting this research has also brought to light some imperfections, as well as the limitations of the results of this research, for example in the measurements of the experiments due to covid-19. These points will be analyzed in this paragraph, together with recommendations for further research.

Initially, my first recommendation will be about the experimental phase. The worldwide outbreak of covid-19 has a result the 1st and the 2nd experiments to finish at 14 days of measurements and the 3rd experiment at 7 days respectively. Since majority of compressive strength gain in mortar/concrete happens at 28th day, the conclusions of this study may have major drawbacks regarding the technical feasibility of RUP, as mechanical properties are examined only up to 14 days. Hence, the first recommendation is full scale experiments to be done in future researches. Also, another useful tool is a calorimetry test for recycled ultrafine particles to be conducted. This procedure will help for better comprehension of the hydration of the recycled cement paste. Furthermore, it will be beneficial for the understanding of these kind of experiments, an addition microscopical analysis to be done in the lab in order to investigate the structure and the shape of recycled sand and recycled cement paste both in hydrated and dehydrated phase in contrast to natural sand and cement particles. From this procedure, useful results will be revealed that would help at the same moment to explain the high water absorptivity of recycled sand particles and recycled ultrafine particles. Moreover, a good point for further research in the experimental phase is the impact of recycled sand to be studied further. It seems that some parameters went wrong in this research. It is recommended that the amount of recycled sand that replaced natural should be less in the future experiments. The 100% substitution was very optimistic, because recycled sand particles have very high water absorption. Also, the amount of mixing water is very crucial. The right quantity can prevent from the zero slump and simultaneously from the early stage hydration helping the mortars to gain flexural and compressive strength over time. The extra water can compensate the high water absorptivity of recycled sand particles in the mixing.

The second recommendation is about the ecological plan. It is suggested more research to be conducted about the ecological benefits from the reduction of gases emissions and especially CO_2. It would be vital maybe the benefits from the ecological approach in this research to be compared to other CO_2 reducing alternatives in mortar/concrete industry. Hence, more studies about the benefits in the maintenance of natural habitat and check of sustainable development approach.

The last recommendation is about more investigation about the opportunities of the creation of a new market for the recycled products like aggregates, sand and cement paste. The simulation of an economic analysis of a potential recycling plants with separation of ultrafine particles gives an evidence of important economic benefits and feasible payback period. It is recommended a further research, which will include the calculation of the taxations and more detailed operation costs, hence a more specific cash-flow analysis about the present and the future. A step that will contribute to the promotion of these products in the concrete market leading more to more circular economy.

Appendices

Extra tables and figures from the research

Size	Fraction %
5,6mm	2%
4mm	3%
2mm	9%
1mm	14%
0,5mm	31%
0,250mm	34%
0,125	9%

Table A: The natural sand size distribution

Size	Fraction %
5,6mm	2%
4mm	3%
2mm	9%
1mm	14%
0,5mm	31%
0,250mm	34%
0,125	9%

Table B: The recycled sand size distribution

Averages	strength MPa			
Flexural Strength				
	day 1	day7	day14	day28
CEM 1	5,5	6,9	7,7	
CEM 1-5%RUP	5,6	7,8	8,9	
CEM1-10%RUP	4,5	6,1	8,0	
CEM1-15%RUP	4,1	6,0	6,9	

Table C Average values of the measurement of the flexural strength of the 1st experiment

Averages	Strength MPa			
Compressive Strength				
	day 1	day7	day14	day28
CEM 1	21,4	38,6	46,3	
CEM 1-5%RUP	22,4	40,1	44,2	
CEM1-10%RUP	16,5	33,5	39,5	
CEM1-15%RUP	15,3	34,4	38,4	

Table D Average values of the measurement of the compressive strength of the 1st experiment

Averages	Strength MPa			
Flexural Strength				
	day 1	day7	day14	day28
CEM 1	5,5	6,9	7,7	
CEM 1-5%RUP	4,0	6,9	8,2	
CEM1-10%RUP	4,1	6,7	8,1	
CEM1-15%RUP	3,9	6,6	7,8	

Table E Average values of the measurement of the flexural strength of the 2nd experiment

Averages	Max.Strength MPa			
Compressive Strength				
	day 1	day7	day14	day28
CEM 1	20,3	38,6	46,3	
CEM 1-5%RUP	19,5	34,5	39,8	
CEM1-10%RUP	17,2	37,0	40,7	
CEM1-15%RUP	14,3	32,4	39,3	

Table F Average values of the measurement of the compressive strength of the 2nd experiment

Averages	Strength MPa			
Flexural Strength				
	day 1	day7	day14	day28
CEM 1	5,5	6,9	7,7	
CEM 1-RS	2,3	5,9		
CEM 1-5%RUP-RS	1,7	5,1		
CEM1-10%RUP-RS	1,5	5,1		
CEM1-15%RUP-RS	0,8	3,9		

Table G Average values of the measurement of the flexural strength of the 3rd experiment

Averages	Strength MPa			
Compressive Strength				
	day 1	day7	day14	day28
CEM 1	21,4	38,6	46,3	
CEM 1-RS	29,3	22,6		
CEM 1-5%RUP-RS	21,9	20,5		
CEM1-10%RUP-RS	16,1	16,8		
CEM1-15%RUP-RS	10,4	13,7		

Table H Average values of the measurement of the compressive strength of the 3rdexperiment

Abbreviations

ADR: Advanced Dry Recovery

CBA: Cost- Benefit Analysis

CDW/C&D WASTE: Construction and Demolition Waste

CFA: Cash-Flow Analysis

CRCA: Coarse Recycled Concrete Aggregates

EU: European Union

FNA: Fine Natural Aggregates

FRCA: Fine Recycled Concrete Aggregates

HAS: Heating Air-classification System

NA: Natural Aggregates

NPV: Net Present Value

RCA: Recycled Concrete Aggregates

RS: Recycled Sand

RUP: Recycled Ultrafine Particles

w/b ratio: water/binder ratio

w/c ratio: water/cement ratio

WACC: weighted average cost of capital

Bibliography

1. © Accro-tech Scientific Industries. (2019). *© Accro-tech Scientific Industries.* Retrieved from https://www.indiamart.com/soiltestingindia/concrete-testing-equipments.html

2. © Ashville Aggregates LTD. (2020, December 7). Reject sand. Retrieved from Aggregates Supplier: https://www.aggregatessupplier.com/product/reject-sand/

3. Amsterdam, G. (2020, September 01). *Property value*. Retrieved from maps amsterdam: https://maps.amsterdam.nl/woningwaarde/?LANG=en

4. Bakker, M. (2014, March 25). Origins of concrete waste overwview of the main waste sources. Delft, The Netherlands.

5. Beaulieu, D. (2020, 02 02). *the spruce*. Retrieved from the spruce: https://www.thespruce.com/difference-between-cement-concrete-and-mortar-2130884

6. Busari A, Adeyanju E, Loto T, Ademola D. Recycled Aggregate in Pavement Construction : Review of Literatures Recycled Aggregate in Pavement Construction : Review of Literatures. 2019. doi:10.1088/1742-6596/1378/2/022026
J. Phys.: Conf. Ser. 1378 022026

7. Claude Goguen. (2014, September 01). *National Precast Concrete Association / Concrete bleeding*. Retrieved from NPCA: https://precast.org/2014/09/concrete-bleeding

8. DELFT_Concrete_Lab, T. (2020, February 20). Size distribution of natural sand particles. Delft, The Netherlands: TU DELFT CONCRETE LAB.

9. EUROPEAN COMMISSION (2006), Integrated Pollution Prevention and Control: Reference Document on the Best Available Techniques for Waste Incineration

10. L. Evangelista & J. de Brito (2014) Concrete with fine recycled aggregates: a review, European Journal of Environmental and Civil Engineering, 18:2, 129-172,8189
https://doi.org/10.1080/19648189.2013.851038

11. Gebremariam AT, Maio F Di, Lotfi S. Advancements in recycling of end-of-life concrete. CPI – Concrete Plant International – 3 | 2018
https://www.cpi-worldwide.com

12. Gorjinia A, Shafigh P, Moghimi M, Bin H. The role of 0 – 2 mm fine recycled concrete aggregate on the compressive and splitting tensile strengths of recycled concrete aggregate concrete. *J Mater*. 2014;64:345-354. doi:10.1016/j.matdes.2014.07.048

13. Goodland R, Bank W. Sustainability : Human , Social , Economic and Environmental. 2002. WorldBank, Washington, DC, USA. Article from Encyclopedia of Global Environmental Change. Copyright © 2002 John Wiley & Sons, Ltd

14. Harlow, K. C. (2018). Integration of Cost-Benefit and Financial Analysis in Project Evaluation. Στο K. C. Harlow, *Integration of Cost-Benefit and Financial Analysis in Project Evaluation volume:48* (pg. 918-928). Houston: Rice university.

15. Hossain U, Sun C, Lo IMC, Cheng JCP. Resources , Conservation and Recycling Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *"Resources, Conserv Recycl*. 2016;109:67-77. doi:10.1016/j.resconrec.2016.02.009

16. Jae H, Hong J, Kwak H. Cement and Concrete Research Experimental simulation of bleeding under a high concrete column. *Cem Concr Res*. 2014;57:61-69. doi:10.1016/j.cemconres.2013.12.011

17. Kavitha S. Evaluation Of CO_2 Emissions For Green Concrete With High Volume Slag , Recycled Aggregate , Recycled Water. 2018;(October). International Journal of Civil Engineering and Technology (IJCIET) Volume 8, Issue 5, May 2017, pp. 703–708, Article ID: IJCIET_08_05_078 Available online at http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=5 ISSN Print: 0976-6308 and ISSN Online: 0976-6316

18. Lauritzen, E. (1998). The Global Challenge of Recycled Concrete. Sustain Constr Use Recycl Concr Aggreg –. London: Proc Int Symp Held Dep Trade Ind ConfCentre, London,.

19. M. Head, M. L. (2006). The Use of Waste Materials in Construction – Progress Made and Challenges for the Future,. Geotech: 5th ICEG Environ. Geotech. Oppor. Challenges Responsib. Environ. Geotech,.

20. Mahasenan, N., Smith, S., & Humphreys, K. (2003). The Cement Industry and Global Climate Change Current and Potential Future Cement Industry CO2 Emissions. Greenhouse Gas Control Technologies - 6Th International Conference, 9951000. doi: 10.1016/b978-008044276-1/50157-4

21. Mahieux LOP. Reuse of recycled crushed concrete fines as mineral addition in cementitious materials. *Mater Struct*. 2020;49(8):3239-3251. https://doi.org/10.1617/s11527-015-0716-1

22. Majaski, C. (2020, March 26). *Investopedia*. Retrieved from Cost of Capital vs. Discount Rate: What's the Difference?: https://www.investopedia.com/ask/answers/052715/what-difference-between-cost-capital-and-discount

23. Mansa, J. (2020, November 9). *Investopedia*. Retrieved from Net Present Value (NPV): https://www.investopedia.com/terms/n/npv.asp

24. Moreton Bay Recycling. (2019, August 8). Moreton Bay Recycling Information. Retrieved from Comparing recycled concrete aggregate prices with quarry aggregates: https://moretonbayrecycling.com.au/comparing-recycled-concrete-aggregate-prices-with-quarry-aggregates

25. MIND_TOOLS_TEAM. (2020, April 21). *Cost-Benefit Analysis*. Retrieved from MIND TOOLS: https://www.mindtools.com/pages/article/newTED_08.htm

26. Nancy MP, Jan E. The Circular Economy – a new sustainability paradigm ? 2016;44(0). Journal of Cleaner Production (accepted version), http://dx.doi.org/10.1016/j.jclepro.2016.12.048

27. NEN-EN-196-1. (2016). Methods of testing cement - Part 1: Determination of strength. In N. N. NEN-EN 196-1, *NEN-EN 196-1 (en) volume 1* (p. 37). DELFT: TU DELFT.

28. Netherlands Enterprise Agency, R. (2020, January 01). *Environmental investment allowance (MIA)*. Retrieved from Business.gov.nl: https://business.gov.nl/subsidy/environmental-investment-allowance

29. News, L.-C. D. (2019, May 07). *Dutch news*. Retrieved from Dutch news.nl: https://www.dutchnews.nl/features/2019/05/after-a-e30-rise-in-january-dutch-energy-prices-among-highest-in-eu

30. Normalisatie-instituut N. Nen-en 1015-3. 2019;(015). Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table)

31. O WOPAN, Harris JM, Goodwin NR. Reconciling Growth and the Environment. 2003;(March). Tufts University Medford MA 02155, USA © Copyright 2003 Global Development and Environment Institute, Tufts University G-DAE Working Paper No. 03-03: "Reconciling Growth and the Environment" http://ase.tufts.edu/gdae

32. Rates CR. The Filler Effect : The Influence of Filler Content and Surface Area on. 2013;1990:1978-1990. doi:10.1111/jace.12264

33. Rem P,(2016), Recycling of End of Life concrete fines into hardened cement and clean sand. J. of Environmental Protection, 7(06),934 *Circular concrete: an organisational revolution?*

34. Serres N, Braymand S, Feugeas F. Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment. *J Build Eng*. 2016;5:24-33. doi:10.1016/j.jobe.2015.11.004

35. Tam VWY, Soomro M, Catarina A, Evangelista J. A review of recycled aggregate in concrete applications (2000 – 2017). *Constr Build Mater*. 2018;172:272-292. doi:10.1016/j.conbuildmat.2018.03.240

36. Thomas A, Filippov LO. Fractures , fractals and breakage energy of mineral particles. 1999:285-301. Laboratoire ()EnÕironnement et Mineraluegie LEMUMR 7569 CNRS, INPL-ENSG , ´Rue du Doyen M. Roubault, BP40, 54501 VandoeuÕre-les-Nancy Cedex, France `

37. Trucking, D. (2020, November 15). *Freights for transportation Netherlands*. Della Retrieved from Trucking: https://della.eu/en-nl/

38. Volvo (2019). Retrieved 22 October 2019, from https://www.volvotrucks.com/content/dam/volvo/volvo-trucks/markets/global/pdf/ourtrucks/Emis_eng_10110_14001.pdf

39. Wagenmakers, B. (2018, February 28). *DUTCH CORPORATE INCOME TAX.* Ανάκτηση από INTERCOMPANY SOLUTIONS: https://intercompanysolutions.com/dutch-corporate-income-tax/

40. Watkins, T. (2012). An Introduction to Cost Benefit Analysis. San Hose State, USA.

41. Y.Kasai. (1998). By-Products and the Use of Recycled Aggregate in Concrete in Japan. Sustain. Constr. Use Recycl. Concr. Aggreg.,.

42. Zhao Z, Remond S, Damidot D, Xu W. Influence of fine recycled concrete aggregates on the properties of mortars. *Constr Build Mater*. 2015;81:179-186. doi:10.1016/j.conbuildmat.2015.02.037