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Sustainability Assessment of Recycled Aggregate Concrete

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Abstract

This thesis presents a cradle-to-gate Life Cycle Assessment (LCA) of concrete produced with recycled coarse aggregates (RCA) derived from construction and demolition waste. The aim of the study is to evaluate both the mechanical performance and the environmental impacts of replacing natural aggregates with RCA in concrete designed for low to medium strength applications, with particular attention to potential uses in road construction.

The experimental program involved the physical and chemical characterization of different RCA fractions. Standard laboratory tests were carried out on each fraction, and concrete mixes were prepared at laboratory scale. Cubes of 150 × 150 × 150 mm were cast and tested at 28 days following established procedures to assess their mechanical properties.

The LCA was conducted in line with ISO 14040/44 standards, using Ecoinvent datasets supplemented with laboratory-generated data. The functional unit was defined as 1 m^3 of concrete produced and tested under laboratory conditions. Key environmental indicators included global warming potential, energy consumption, and resource depletion. Data processing and analysis were performed using the KNIME platform.

The results show that the mixes made with recycled aggregates were able to meet the mechanical and practical requirements for the intended applications while also achieving noticeable environmental benefits. Compared to the concrete made with natural aggregates, the RCA mix produced around 6–7% less CO_2 emissions, which mainly came from avoiding quarry extraction and reducing transport distances.The total energy demand also dropped by roughly 12–15%, since the recycling process consumes less fuel and electricity than producing virgin aggregates.In terms of water use, the difference was even more visible, the RCA mix required about half as much water, mostly because natural aggregate production involves extensive washing and dust control.

A small increase was observed in the ozone depletion potential, likely related to the higher electricity use during crushing and sorting, but its effect was very limited compared with the overall reductions. Overall, the life-cycle results confirm that recycled concrete aggregate can significantly reduce the environmental footprint of concrete production while maintaining the level of performance required for road and pavement construction.

Overall, this study provides a combined assessment of RCA-based concrete within the Italian context, integrating laboratory experiments with LCA. It identifies the main material properties affecting performance, highlights the environmental trade offs, and offers practical insights for advancing the use of recycled aggregates in sustainable construction practices.

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List of Abbreviations

AI – Artificial Intelligence
BSI - British Standards Institution
C&D – Construction and Demolition
CDW – Construction and Demolition Waste
CO_2–$CarbonDioxideEquivalent$
$CO(fossil)$: $Carbonmonoxide(fossilorigin)$
CS–$CompressiveStrength$
EJ : $Exajoule(aunitofenergy, 1EJ = 10^{18}$ Joules)
EIA – Environmental Impact Assessment
EN – European Norm (Standard)
EPD – Environmental Product Declaration
EU: European Union
FU – Functional Unit
GHG – Greenhouse Gas
ISO – International Organization for Standardization
kWh: Kilowatt-hour
LCA – Life Cycle Assessment
LCCA - life cycle cost analysis LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LCOE: Levelized Cost of Electricity
LHV: Lower Heating Value
MBV – Methylene Blue Value
MJ: Megajoule
NFU: Net Functional Unit
NOx: Nitrogen oxides
MSW – Municipal Solid Waste
NA – Natural Aggregate
RA – Recycled Aggregate
RCA – Recycled Coarse Aggregate
RMSE – Root Mean Square Error
SP – Superplasticizer
UNI – Ente Italiano di Normazione (Italian National Standards Body)
WA – Water Absorption
W/C – Water-to-Cement Ratio

1 Introduction

1.1 Background and Context

The construction industry is one of the largest consumers of natural resources in the world. Large scale infrastructure works such as roads, bridges, and urban developments, require significant quantities of aggregates and cement, which together leave a considerable environmental footprint. As cities expand and transport networks grow, the demand for materials used in base layers, sub-bases, and concrete pavements continues to rise. However, the intensive extraction of natural aggregates (NA) accelerates the depletion of finite geological resources and causes environmental issues such as landscape disturbance, dust generation, and greenhouse gas emissions. These growing concerns have strengthened the search for more sustainable alternatives that can balance environmental protection, economic practicality, and technical performance [1].

Recent data published by the Città Metropolitana di Torino (2024) [2] illustrate this issue at a local scale. The metropolitan area, which has a population of about 2.21 million people (ISTAT, 2021)[3], collected approximately 59,800 tonnes of inert waste in 2023. This material composed mainly of concrete, bricks, ceramics, and stones,represents roughly 27 kilograms per inhabitant per year. Much of it is reused for road foundations, backfilling, or environmental restoration, showing that a local circular system for recovering and reintroducing construction and demolition waste (CDW) is gradually taking shape.

While this figure only reflects the portion of CD waste collected separately, it highlights steady progress in regional recycling practices. These improvements are supported by the circular economy strategies promoted by local authorities, such as those described in Regione Piemonte – AR-Piemonte (2024) [4]. At a national level, Italy has also made notable progress, reaching a recovery rate of around 76–80% for CD waste. This marks a sharp increase from the modest 10–20% recorded in the late 2000s. Such progress has been driven by stricter environmental regulations, the expansion of recycling facilities, and the rising competitiveness of secondary raw materials. Within this framework, the Metropolitan City of Turin has emerged as one of the leading regions promoting circular construction practices, contributing actively to regional goals of 65% recycling and 8% separate waste collection by 2035 .

Across Europe, the recycling of construction and demolition waste (CDW) is encouraged through legislation, national plans, and technical standards. Recycled aggregates are obtained by collecting, cleaning, crushing, and sieving CDW in specialized facilities to meet the quality requirements for construction materials. In northern Italy, CAVIT S.p.A., based in Turin, provides a practical example of these principles in action. The company processes CDW in compliance with European standards, producing recycled aggregates typically ranging from 0 to 40 mm in size, with laboratory samples often sieved to 31.5 mm.

The material produced,known as non selective CDW recycled aggregate (CDW-RA) consists mainly of crushed concrete, reclaimed asphalt, bricks, tiles, and natural stones. Concrete and stone usually make up the majority, reflecting the composition of urban demolition waste. By turning this heterogeneous mix into high quality aggregates suitable for road construction and rehabilitation, CAVIT plays an active role in closing the material loop. Its operations divert large quantities of waste from landfills while providing reliable recycled materials for the market. In doing so, the company helps to conserve natural resources, reduce energy use and emissions, and support the region's transition toward a more circular and resource-efficient construction model [5].

Recycling and reusing construction and demolition waste (CDW) is now widely recognized as one of the most effective ways to reduce the environmental burden of the construction industry. CDW is among the largest waste streams worldwide, consisting mainly of concrete rubble, bricks, ceramics, asphalt, wood, and stones generated during demolition, renovation, or maintenance works. Instead of sending these materials to landfill, modern recycling technologies can process them into CDW recycled aggregates (CDW-RA) that serve as secondary raw materials. This approach fits squarely within the principles of the circular economy, transforming waste into a resource and reducing both extraction and disposal impacts.

Physically, CDW-RA differs from natural aggregates due to its higher porosity, rougher surface texture, and irregular particle shape. These differences can influence mechanical behavior, such as strength and compaction properties. However, many studies have shown that with appropriate processing and quality control, CDW-RA can perform well in a wide range of civil engineering applications, particularly in road construction and structural backfilling [6].

The use of CDW-RA in road construction offers several clear advantages. Recycling requires less energy and generates fewer emissions than extracting and transporting virgin aggregates. It also reduces the need for landfill space and lowers the risk of groundwater contamination caused by leachate. From an economic perspective, using recycled aggregates can help cut costs by reducing the demand for natural materials and avoiding landfill fees. When recycling plants are located close to construction sites, transport distances are shortened, making the process even more cost effective. As natural aggregate prices continue to rise, recycled materials become increasingly competitive and attractive for both contractors and public authorities [7].

To quantify these environmental and economic benefits, Life Cycle Assessment (LCA) is often applied. LCA provides a systematic way to evaluate the environmental impacts of materials and processes over their entire life cycle—from raw material extraction and production to use and disposal. In road construction, it allows direct comparison between natural and recycled aggregates in terms of energy consumption, emissions, and resource efficiency. Existing studies consistently report that recycled aggregates can have lower overall environmental impacts, especially in categories such as global warming potential and non-renewable energy use, provided that transport distances remain limited [8].

Building on this background, the present study applies the LCA approach using local data and process information to obtain context-specific results that reflect the actual conditions of production and recycling in the Turin region. The goal is to evaluate the environmental performance of recycled aggregates compared with natural aggregates under realistic operating scenarios.

1.2 Objectives of the Thesis

The goal of this thesis is to evaluate the viability and durability of incorporating recycled concrete aggregates in place of natural aggregates in concrete. To achieve this, the study identifies the characteristics of RCA by means of standard laboratory tests, which include particle size distribution, water absorption, the flakiness index, the shape index, and contamination analysis. Using these results, laboratory scaled concrete mixes incorporating RCA of varying size fractions (40 mm and 8 mm) are designed to achieve the target strength and workability requirements for road construction. The performance of RCA-based concretes is then assessed through standardized testing on both fresh and hardened concrete at different curing ages. In addition, a Life Cycle Assessment (LCA) was carried out to evaluate the environmental impacts of RCA concrete in comparison with conventional concrete made with natural aggregates, considering all stages from raw material extraction or recycling up to the production of 1 m^3 of concrete at the plant gate. Ultimately, this thesis aims to offer actionable conclusions and directions on the use of RCA for the construction of sustainable infrastructures, demonstrating their environmental benefits to support the circular economy within the Italian construction market.

In this thesis, the environmental performance of RCA-based concrete is evaluated using a Life Cycle Assessment (LCA) framework in accordance with ISO 14040/44.To capture the main sustainability trade-offs, multiple midpoint impact categories from the EF v3.1 method are considered, including:

- **Climate change** (kg CO_2-eq)
- **Energy resources, non-renewable (fossil)** (MJ)
- **Water use** (m^3 world eq.)
- **Ozone depletion** (kg CFC-11-eq)

1.3 Thesis Structure

Chapter 1 – Introduction

This chapter shows the background and motivation of the study, highlighting the challenges of natural aggregate consumption, the potential of recycled coarse aggregates from construction and demolition waste, and the sustainability issues examined in this thesis.

Chapter 2 – Literature Review

This chapter reviews the use of CDW and RCA in concrete as reported in previous literature. It shows the physical and mechanical properties of RCA, and how it affects the concrete, as well as the sustainability benefits and limitations highlighted in the literature.

Chapter 3 – Materials and Methods

In this chapter provides an analysis of recycled aggregates, including material collection, processing, and characterization.

Chapter 4 – LCA Methodology

Defines the goal, scope, boundaries, functional unit, data sources, and impact assessment methods. Summarize modeling assumptions and their justification.

Chapter 5 – Results

This chapter presents the experimental and LCA results, including the physical and mechanical properties of RCA, the performance of RCA-based concrete, and the evaluated environmental benefits of RCA adoption.

Chapter 6 – Discussion

Critical analysis of the results, comparing them with findings from existing literature. It discusses the implications for performance, sustainability, and practical application of RCA in concrete and roadway construction.

Chapter 7 – Conclusions and Recommendations

This chapter Summaries key outcomes, provides final conclusions on the environmental feasibility of the proposed system, and offers recommendations for future research.

2 Literature Review

2.1 Construction Waste, Recycled Aggregates and Life Cycle Assessment

The construction sector is one of the main drivers of resource use and waste generation in Europe.
Eurostat data show that construction and demolition activities, together with mining and quarrying, account for the majority of total waste produced in the European Union, much of it in the form of mineral waste and soils [9].
This means that large volumes of rock, gravel, sand and concrete are continuously extracted, used, and then discarded, often after relatively short service lives.
At the same time, the sector is responsible for a substantial share of raw material consumption, with estimates indicating that almost half of all extracted non-renewable materials are linked in some way to construction works [10].
The pressure on natural landscapes, energy demand and emissions makes this sector a priority area for circular economy strategies.

Italy broadly follows this European pattern.National data report that construction and demolition waste (CDW) represents a large fraction of the total special waste produced each year, with values on the order of 80 million tonnes [11].
On a per capita basis, the need for construction materials is estimated between 6 and 11 t per year, whereas the per-capita generation of CDW is around 0.8 t per year [10].
These figures indicate that, even if all CDW could be recycled, the potential share of recycled aggregates (RA) in the national aggregate market would be limited to roughly 7–13%, depending on the efficiency and quality of recycling processes [10].In practice, technical, regulatory and market barriers reduce this potential even further.

Although the European Waste Framework Directive (2008/98/EC) set a target of at least 70% recycling and recovery of CDW by 2020, the situation on the ground has been more complex.Earlier Italian assessments reported that more than 80% of inert waste still went to landfill, and illegal dumping remained an issue in some regions [12].
Landfill space is limited, and the environmental impacts of quarrying and waste disposal are increasingly contested.For these reasons, many European countries, including Italy, have begun to shift from simple disposal toward recovery and reuse of CDW.
The Directive explicitly encourages viewing CDW as a source of secondary raw materials, rather than a residual to be managed.Italy has implemented this shift through instruments such as the Legislative Decree of 11 October 2017 and the Italian Structural Code (NTC 2018), which allow and in some cases require partial or full replacement of natural aggregates (NA) with recycled aggregates (RA) in public works [13, 14].
These measures aim to reduce the demand for virgin aggregates and support more circular construction practices.

Recycled aggregates, and in particular recycled concrete aggregates (RCA), differ from natural aggregates mainly because they retain a layer of old mortar on their surface.
This residual mortar increases porosity and water absorption, and generally reduces density and mechanical strength compared with natural gravel or crushed rock [15].
However, these differences do not automatically prevent their use in concrete; they simply require that mix design and quality control be adapted.

Silva et al. [15] showed that the properties of RCA are strongly influenced by the original concrete: aggregates derived from high-strength, low water–cement ratio concretes tend to have higher dry density, lower water absorption and better resistance to fragmentation than those obtained from poorer-quality sources.
There is therefore a direct link between the quality of the parent concrete and the performance of the recycled aggregate.

Several classifications have been proposed in the literature to distinguish between different types of recycled aggregates.
RCA typically refers to aggregates in which at least 90% by mass consists of concrete and natural stone fragments, while recycled masonry aggregates (RMA) and mixed recycled aggregates (MRA) contain significant proportions of bricks, tiles and other masonry materials [16, 15]. Some authors also use the broader term CDW recycled aggregates (CDRA) when dealing with heterogeneous materials that may include contaminants such as glass, plastic or wood [15].
From the point of view of bulk density, most of these materials fall into the category of normal-weight aggregates, alongside natural sands and gravels and some industrial by-products such as blast-furnace slag or recycled glass.

Using RCA is closely connected with the principles of sustainable development.The classic definition in the Brundtland Report describes sustainable development as meeting present needs without compromising the ability of future generations to meet their own [17].
Later definitions by IUCN and ASCE emphasise living within the carrying capacity of ecosystems and balancing human needs for infrastructure, energy and materials with environmental protection [18, 19].
Recycling CDW contributes directly to these goals: each tonne of recycled aggregate reduces the need for new quarry extraction and avoids a tonne of material going to landfill.
In many cases, using local CDW recycling reduces transport distances and associated fuel consumption [20, 21]. These effects align with several of the United Nations Sustainable Development Goals, particularly those related to sustainable cities, responsible consumption and resilient infrastructure.

From a technical perspective, a substantial body of research shows that RCA can perform adequately in many applications when properly processed and used. Mechanical tests such as the Los Angeles Abrasion (LAA) and Aggregate Impact Value (AIV) often place good-quality RCA in strength classes suitable for base and sub-base layers or low- to medium-strength concrete [15].
In some studies, RCA with LAA values around 20–25% and AIV values below 10% have been classified as “strong” or “exceptionally strong” aggregates [20].
When RCA and recycled sand are used together in concrete, compressive strengths close to or above the design strength can be achieved, provided that the mix design accounts for higher water absorption and that suitable admixtures are used.
Microstructural observations using scanning electron microscopy often show a dense interfacial transition zone between the new cement paste and the RCA particles when appropriate curing and mix proportions are adopted [15].

The potential environmental benefits of using CDW aggregates have been explored by several life cycle assessment (LCA) studies. Many of these focus on comparing recycling with landfilling, or on assessing scenarios in which CDW aggregates replace natural aggregates in concrete or road pavements [20, 21].

Blengini and Garbarino [20], for example, analysed resource and waste management in the Turin area and showed that producing RA from CDW can reduce greenhouse gas emissions and non-renewable energy use, particularly when local recycling plants and quarries are considered. Zhao et al. [21] examined the use of CDW aggregates stabilised with cement and cement kiln dust (CKD) in road base layers and found significant environmental and economic benefits due to lower energy consumption, reduced emissions during material processing, and decreased landfill disposal.

At the same time, the literature stresses that LCA results for aggregates and CDW management are sensitive to methodological choices and local conditions.
ISO 14040 and ISO 14044 define LCA as a cradle-to-grave method, but in waste management studies the system boundaries are often adapted to cradle-to-gate or gate-to-gate approaches, focusing on collection, recycling and substitution of natural resources [22, 23, 24]. Concepts such as the “zero burden” assumption, where the environmental loads of the original product are not attributed to the waste, are commonly used but remain debated [25].
Several authors argue that mining and recycling impacts are highly site dependent and that using only national average data may hide important local variations [26, 27].
For this reason, studies such as those carried out in the Turin region, which combine local inventory data with LCA modelling, are particularly valuable [20].
They show how the real environmental performance of RCA depends not only on the material itself, but also on transport distances, plant efficiency, energy mixes, and the specific applications in which the aggregates are used.

2.2 Properties and Classification of Recycled Aggregates

Recycled aggregates are different from natural ones mainly because they carry a layer of old mortar on their surface. This mortar makes them slightly more porous and lighter, which increases water absorption and affects mechanical behavior. Several studies mention that recycled aggregates tend to have lower density and slightly higher fragility than natural aggregates.[28] However, these differences do not mean they cannot be used in concrete; they only require proper mix design and processing to achieve good performance.

The properties of recycled concrete aggregates (RCA) depend heavily on the original concrete they come from. According to Silva et al. (2014)[29], RCA made from strong concrete with a low water-to-cement ratio usually shows better density, lower absorption, and greater resistance to crushing. This means that the quality of the parent concrete directly affects the performance of the recycled aggregate. It also highlights the importance of careful demolition and sorting so that high-quality materials can be recovered efficiently.

Aggregates are commonly grouped by their density:

- **Normal-weight aggregates:** most sands, gravels, and crushed stones such as granite, basalt, and limestone;
- **Lightweight aggregates:** materials such as expanded clay, pumice, or volcanic rock, used where reduced weight is required;
- **Heavyweight aggregates:** dense minerals such as barite or magnetite, used mainly for radiation shielding or special concrete.

Recycled aggregates usually fall into the first category, as their overall density remains close to that of natural materials. Some industrial by-products, like blast-furnace slag or recycled glass, are also classed as normal-weight and share similar applications in sustainable concrete.

2.3 Recycled Aggregates and Sustainable Development

Using recycled aggregates is closely connected with the idea of sustainable development. The Brundtland Report defined it as meeting present needs without limiting the ability of future generations to meet their own. Later, the International Union for Conservation of Nature (1991) described it as “improving the quality of human life while living within the carrying capacity of ecosystems,” while the American Society of Civil Engineers (1996) emphasized the balance between human needs and environmental quality.[8]

Recycling CDW fits these definitions well. Every tonne of material that is reused means less extraction of new natural resources and less waste going to landfill. In many cases, local recycling also reduces transport distances and the energy that goes with them. These actions contribute directly to several of the United Nations Sustainable Development Goals—particularly Goals 9, 11, and 12—which focus on resilient infrastructure, sustainable cities, and responsible consumption.

2.4 Benefits of Using Recycled Concrete Aggregates

A growing number of studies show that RCA can perform well in practical applications. However, the performance of recycled concrete aggregate depends strongly on its composition, which is mainly influenced by the quality of the parent concrete, the proportion of adhered mortar, and the presence of contaminants such as brick, asphalt, or gypsum. In this study, the RCA used consists of crushed structural concrete waste with a low content of impurities and a moderate amount of adhered mortar, which classifies it as Type I (high-quality RCA) according to common classifications in the literature. With proper processing, its mechanical and durability properties can approach those of concrete made with natural aggregates. For instance, recycled aggregates with an Aggregate Impact Value (AIV) of 5.76% fall into the "exceptionally strong" category according to BS 812-110.[30] The Los Angeles Abrasion Value (LAA) of 21.78% confirms strong resistance to wear, making this type of RCA suitable for pavements and structural concrete.

When RCA and recycled sand are used together in M20 grade concrete, the average compressive strength reaches about 26.2 N/mm², which slightly exceeds the design strength of 25 N/mm². Durability tests also give good results: soundness expansion was limited to 0.53 mm, showing stable behavior under environmental changes. Microscopic observations using Scanning Electron Microscopy (SEM) revealed a solid bond between the cement paste and the RCA particles, producing a dense interfacial transition zone (ITZ) that contributes to long-term strength.[31]

From an environmental point of view, using RCA cuts down the demand for natural aggregates and reduces carbon emissions from extraction and transport. It also decreases the amount of waste sent to landfill, which is an important issue in regions with limited disposal space. These effects fit perfectly within the circular economy model now promoted across Europe.

Economically, the benefits are also clear. Recycled materials can reduce overall costs by lowering both raw-material expenses and landfill charges. As the cost of quarrying and transportation continues to rise, RCA becomes increasingly competitive. It also supports local recycling companies and encourages technological innovation in waste processing.

Taken together, these findings show that recycled concrete aggregates can offer real technical, environmental, and economic value when used correctly. Continued research, better sorting at demolition sites, and quality control in recycling plants will help increase their acceptance and reliability within the construction sector.

3 Materials and Methods

3.1 Case Study

The case study developed for this research is based in the city of Torino, located in the northwestern region of Italy. This area has become a significant center for construction and demolition waste (CDW) management within the Piedmont region, where sustainable construction practices have gained increasing attention in recent years. The recycling facility chosen for this study plays an important role in promoting a circular approach to construction materials, transforming waste from demolition activities into usable aggregates for new infrastructure projects.

Figure 3.1: General view of the CDW recycling facility in Torino, Piedmont region

Most of the materials used in this research were collected from various construction and demolition sites distributed across the province of Piedmont. These include building demolitions, renovation projects, and road maintenance works, all of which generate considerable amounts of concrete, masonry, and mixed debris. After collection, the materials are transported to the recycling facility near Torino, which serves as a central processing site for CDW management in the region. Each load of waste is first inspected, weighed, and recorded to maintain proper documentation and traceability before the recycling process begins.

Once the materials arrive at the facility, they undergo a systematic series of operations aimed at recovering only the mineral components suitable for engineering use. The waste is first passed through specialized mechanical screening equipment mounted on heavy-duty vehicles. This process separates the materials based on particle size and composition. Fine soils are screened out initially, and larger fragments such as stones, concrete pieces, and bricks are isolated for further processing. During this stage, unwanted impurities such as paper, plastics, wood, and other non construction waste are carefully removed, both manually and mechanically. Additional attention is given to eliminating materials like glass, metals, and asphalt that could interfere with the quality of the final product.

After cleaning and sorting, the remaining mineral materials are crushed and sieved into different size categories, typically ranging from 0–8 mm, 8–25 mm, and up to 40 mm. This classification is essential to ensure that the recycled aggregates meet the technical specifications required for different construction purposes. In this research, two size fractions—0–8 mm and 0–40 mm—were selected for further laboratory testing. The 0–8 mm fraction represents the fine material, while the 0–40 mm fraction contains both fine and coarse aggregates. These selected materials were later used in concrete preparation and testing to evaluate their performance in road construction applications.

Figure 3.2: Recycled aggregate materials after separation and screening

The cement used for producing the concrete mixtures is also sourced locally within the Piedmont region. Ordinary Portland Cement from nearby suppliers is delivered directly to the facility, reducing transportation distances and supporting a sustainable production chain. This local sourcing approach reflects the overall philosophy of the case study, which aims to minimize environmental impact while maximizing the reuse of regional resources.

The recycled aggregates produced at the Torino facility are mainly used for road construction, particularly in the base and sub-base layers of pavement structures. These layers play a crucial role in distributing loads and ensuring the long-term durability of the roadway. By replacing natural aggregates with recycled coarse aggregates (RCA) derived from CDW, the study evaluates not only the mechanical performance of the resulting concrete but also its environmental and economic advantages.

This case study represents real operational conditions found in northern Italy, where CDW management is both a practical challenge and a policy priority. The processes observed at the Torino facility demonstrate how efficient waste recovery and reuse can contribute to sustainable development goals, resource conservation, and the reduction of landfill disposal. Through the analysis of this case, the research aims to provide valuable insights into the feasibility and long-term performance of recycled aggregates in concrete applications, particularly for road infrastructure.

In this study, two types of recycled aggregate fractions obtained from the Torino recycling facility were selected for testing: 0–8 mm and 0–40 mm. These size ranges represent fine and coarse recycled aggregates that are typically used in roadway and concrete applications. The selected materials were subjected to a series of physical and mechanical tests to evaluate their suitability for use in concrete production. The following sections describe the testing procedures, concrete preparation process, and subsequent experimental evaluation of the produced mixes.

3.2 Testing of Recycled Aggregates

Before incorporating recycled aggregates into concrete mixtures, several laboratory tests were performed to understand their physical and mechanical behavior. These tests help to compare recycled materials with natural aggregates and ensure that they meet the required standards. All procedures followed the main European Standards (EN) that define how aggregate properties should be determined. The analysis mainly focused on two size fractions, 0-8 mm and 0-40 mm, both obtained from the CDW recycling plant in Torino.

According to EN 206 [32], aggregates used in concrete,whether natural or recycled, must satisfy certain quality and performance limits before use. The standard specifies requirements for properties such as grading, density, water absorption, and levels of impurities, which are important for the durability and consistency of concrete. It also highlights the importance of checking and testing recycled materials before mixing to make sure that they behave in a way similar to natural aggregates. Following these recommendations helped ensure that the recycled aggregates used in this study were suitable for concrete production under European conditions.

By following the specifications and recommendations of EN 12620[33], this research ensured that the recycled aggregates used in the experimental program complied with the necessary European quality and performance standards. Adhering to these guidelines helped maintain consistency and reliability in testing results, while also allowing a fair comparison between natural and recycled materials. Furthermore, the use of standardized testing procedures contributed to a better understanding of how the physical and mechanical behavior of recycled aggregates aligns with that of conventional natural aggregates under similar conditions.

3.2.1 Particle Size Distribution

The particle size distribution test was performed according to EN 933-1[34]. This test aims to determine the proportion of different particle sizes within the sample and to evaluate whether the material meets the grading requirements for use in the production of concrete and the pavement layers.

Figure 3.3: Sieving machine used for particle size distribution testing of recycled aggregates

For the 0–40 mm sample, the materials were first spread evenly on a clean surface to allow uniform sampling. The coning and quartering method (a common manual technique for sample reduction) was applied to divide the aggregate pile into four equal portions. Two diagonally opposite quarters were selected and combined to obtain a representative sample for testing. The selected portion was then oven-dried to remove moisture content.

The dry weight of the 0–40 mm sample was 3.000 kg, and the wet weight was 3.090 kg, resulting in a water content of approximately 3%. After drying, the sample was sieved using a set of standard sieves ranging from 50 mm to 0.063 mm. Each retained fraction was carefully weighed and recorded. The results showed that the material consisted of approximately 73.88% gravel, 19.88% sand, and 6.24% fines. According to the particle size distribution curve figure 3.4, the recycled aggregates exhibit a well-graded structure within the coarse fraction, confirming that the material is predominantly gravel-sized particles with a relatively low proportion of fines. This grading supports the suitability of the recycled coarse aggregates for structural concrete applications.

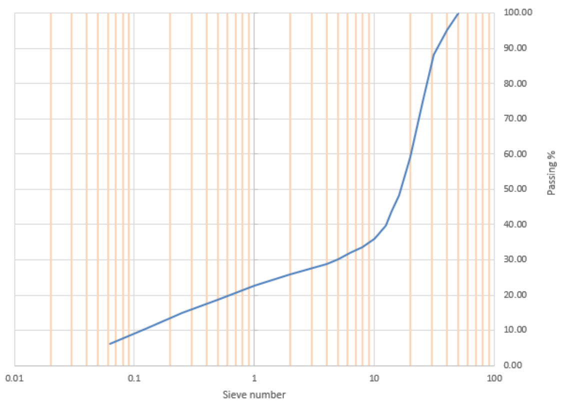

Figure 3.4: Particle size distribution curve of the 0–40 mm recycled aggregate sample

For the 0–8 mm sample, the same procedure was followed. The material was first reduced using the quartering technique to ensure that a representative sample was obtained. The dry weight of this portion was 1.500 kg, while the wet weight was 1.570 kg, indicating a water absorption of approximately 3%. The sample was then sieved through a series of standard sieves ranging from 10 mm down to 0.063 mm, and the retained fractions were weighed and documented. According to the grading curve presented in Figure 3.5, the 0–8 mm material contains a higher proportion of sand-sized particles with limited fines, placing it within the acceptable range of the standard gradation limits specified by EN 933-1. This confirms that the material exhibits suitable particle size characteristics for use as recycled fine aggregate, although the proportion of fines should be monitored to ensure compliance with the requirements for concrete applications.

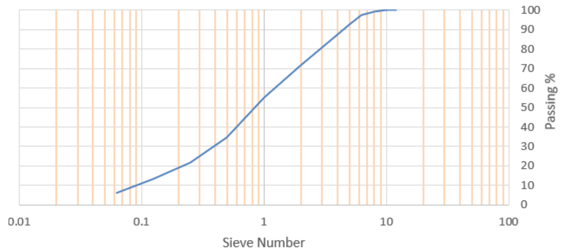

Figure 3.5: Particle size distribution curve of the 0–8 mm recycled aggregate sample

The 24-hour oven-drying process ensured that the moisture content results were accurate, which is particularly important for recycled aggregates, as they generally exhibit higher water absorption due to the presence of old mortar and micro-cracks on their surfaces. The obtained results confirm that both size fractions fall within acceptable grading limits for use in concrete applications, though the higher fines and absorption rates highlight the typical characteristics of recycled aggregates when compared to natural ones.

Figure 3.6: Recycled aggregate soil sample prepared for laboratory testing

3.2.2 Classification of Constituents of Coarse Recycled Aggregate

After determining the particle size distribution, a classification test was carried out to identify and quantify the main constituents of the RCA. This test is essential to evaluate the composition and quality of recycled materials, as they typically contain a mixture of different construction waste components such as concrete, bricks, ceramics, asphalt, and minor impurities. The identification of each constituent helps determine the suitability of the recycled aggregate for use in concrete production and other structural applications.

The test procedure was performed in accordance with EN 933-11[35]. According to this standard, the recycled aggregate sample is visually examined and manually sorted into different material categories. The main recognized categories include:

Rc – Concrete and unbound natural aggregates
Rb – Clay masonry, bricks, and ceramics
Ra – Bituminous materials
Rg – Glass
X – Other impurities (such as gypsum, metals, and plastics)

In this study, the coarse fraction of the recycled aggregate (0–40 mm) was selected for visual composition analysis. The test was performed on a representative oven-dried sample obtained after the sieving stage. Each particle was manually classified into the corresponding material category based on visual appearance, color, texture, and hardness. After separation, the mass of each category was recorded using a precision balance, and the relative proportions were determined by comparing the weight of each constituent to the total sample mass. As illustrated inTable 3.1, the majority of the material consists of high-quality concrete fragments, with smaller quantities of brick, mortar, and other minor impurities, confirming that the recycled aggregate is predominantly derived from structural concrete and falls within the acceptable limits for high-quality RCA.

The results of the classification test are summarized as follows:

Rc + Rg (Concrete and natural aggregate): 72.74%

Rb (Brick and ceramic materials): 26.34%

X (Other impurities): 0.92%

Table 3.1: Percentage Composition of Materials by Sieve Size

Sieve Number	Concrete (%)	Brick (%)	Tiles (%)	Impurities (%)
40	59.13	40.87	0.00	0.00
31.5	68.92	18.44	11.26	0.31
25.4	77.66	18.22	3.26	0.15
20	72.94	21.48	4.29	0.00
16	87.51	9.91	2.32	0.26
12.5	62.62	30.18	5.21	0.44
10	79.08	21.33	0.00	0.27
8	70.84	26.76	0.00	1.02
6.3	68.61	28.64	0.00	0.55
5	62.15	28.68	8.60	0.30
4	74.93	15.59	7.73	0.61
Overall	**72.74**	**21.03**	**5.31**	**0.92**

These results indicate that the recycled aggregate sample is predominantly composed of concrete and natural stone particles, representing nearly three-quarters of the total mass. The presence of brick and ceramic fragments is relatively high but still within acceptable limits according to the EN 933-11 standard, which allows their use in concrete and road applications if the total amount of Rb does not exceed the threshold defined for the intended use. The impurity content (0.92%) is very low, suggesting that the cleaning and screening process performed at the recycling facility was effective in removing unwanted materials such as glass, metal, and plastics.

The classification results demonstrate that the coarse recycled aggregate (RCA) obtained from the Torino recycling facility meets the quality requirements for use in concrete production and roadway applications, aligning with the material composition typically found in non-selective CDW recycling processes.

3.2.3 Determination of Flakiness and Shape Index of Recycled Aggregates

To further understand the geometrical characteristics of the coarse recycled aggregates used in this study, two shape-related tests were carried out: the Flakiness Index and the Shape Index. These parameters play an important role in assessing the quality of aggregates for concrete production and pavement construction. The overall shape and proportion of elongated or flaky particles significantly influence compaction, workability, and the strength of the final concrete mix. Aggregates with irregular shapes tend to create voids, reduce interlocking, and lead to higher cement demand; therefore, determining these indices is necessary to ensure that the recycled aggregates meet the technical requirements for structural use.

Both tests were performed on the 0–40 mm coarse recycled aggregate fraction obtained from the Torino recycling facility. Before the tests, the aggregates were cleaned, oven dried, and sieved to remove particles smaller than 6.3 mm, as the standards specify that only coarser particles are considered in shape analysis. The procedures followed the European standards EN 933-3:2012 [36] for the Determination of Flakiness Index and EN 933-4[37] for the Determination of Shape Index.

The apparatus used for both tests included a standard set of test sieves, a metal flakiness gauge with precisely cut slots for each nominal aggregate size, a shape index caliper, and a digital balance for mass measurement. The same representative sample used for the previous classification test was employed here to maintain consistency in analysis.

The test samples consisted of the 0–40 mm coarse recycled aggregate fraction previously dried and classified. Before testing, all particles larger than 6.3 mm were carefully separated, as required by the standard procedure.

Flakiness Index Test

For the Flakiness Index, the aggregates were first divided into size groups according to the sieves specified in EN 933-3[38]. Each group was then tested separately. Individual particles from each fraction were passed through the corresponding slot in the flakiness gauge. The gauge allows only particles whose thickness is less than 0.6 times their mean size to pass through. These are considered "flaky" particles. The remaining, thicker particles are classified as regular. After separating the flaky particles, both the total sample weight and the flaky fraction weight were recorded using the precision balance. The percentage of flaky particles was then calculated using the formula:

Figure 3.7: Bar sieves used for determining the flakiness index of recycled coarse aggregates

$$\mathrm{FI}(\%) = \frac{W_t}{W_f} \times 100$$

where:

W_f = mass of flaky particles (g)

W_t = total mass of the sample (g)

Throughout this process, special care was taken to handle the particles gently, as recycled aggregates often possess weaker edges due to adhered mortar and previous crushing. After calculating the values for all sieve fractions, the detailed results are presented in Table 3.2, expressed as the percentage of flaky particles for each size range. The average Flakiness Index was found to be 16.70%, indicating that the recycled aggregate contains a relatively low proportion of thin, plate-like particles. In practice, this suggests that the material is capable of achieving good compaction and stable packing when used in concrete or sub-base pavement applications. The obtained value lies within the acceptable limits for recycled aggregates according to EN specifications and is consistent with the range reported in previous studies for construction and demolition waste–derived aggregates.

Table 3.2: Flakiness Index of Recycled Coarse Aggregate

Sieve Size (mm)	Bar Sieve (g)	Flakiness Index (%)
50	0.00	0.00
40	0.00	0.00
31.5	66.34	31.65
25.4	87.09	21.83
20	51.76	11.08
16	52.05	15.99
14	0.00	0.00
12.5	17.42	14.34
10	18.56	16.54
8	12.69	18.17
6.3	11.25	22.90
5	10.50	18.73
4	5.04	13.91

Shape Index Test

The shape index test was carried out to evaluate the geometric characteristics of the recycled coarse aggregates and to assess the degree of particle elongation within the material. This property is important because the shape of aggregate particles has a direct effect on the workability, compaction, and overall mechanical behavior of the resulting concrete or pavement layers. Irregular or elongated particles can negatively influence packing density and increase void content, which in turn affects strength and durability.

The procedure was conducted in accordance with the EN 933-4[37]. In this method, a representative sample of recycled coarse aggregate, previously cleaned and oven-dried, was selected and divided into appropriate size fractions. Each fraction was then tested individually to ensure accurate results across the full size range of the material.

A shape index caliper was used to measure the elongation of individual particles. For each particle, the smallest dimension (thickness) and the largest dimension (length) were determined using the calibrated caliper. The ratio of these two measurements was then compared to the limit values specified in the standard. Particles that exceeded the threshold for elongation meaning they were significantly longer relative to their thickness, were classified as elongated and recorded separately.

Figure 3.8: Shape index caliper used for measuring the elongation of recycled coarse aggregate particles

All particles classified as elongated were collected and weighed. The Shape Index was then determined by comparing the mass of elongated particles to the total sample mass, using the formula:

$$\mathrm{SI}(\%) = \frac{W_e}{W_t} \times 100$$

where:
W_e = mass of elongated particles (g)
W_t = total mass of the sample (g)
From this test, the Shape Index of the recycled coarse aggregate was measured as 24.03%, representing the overall percentage of elongated particles in the sample. The detailed results for each particle size fraction are presented in Table 3.3, expressed as the percentage of elongated particles retained on each sieve. This indicates a moderate proportion of elongated particles within the material, which is a typical characteristic of recycled aggregates produced through mechanical crushing processes. Although recycled aggregates often exhibit slightly higher shape irregularity compared to natural aggregates, the obtained values fall well within acceptable limits for use in structural concrete applications.

Table 3.3: Shape Index of Recycled Coarse Aggregate

Sieve Size (mm)	**Non-Cubical (g)**	**Shape Index (%)**
50	0.00	0.00
40	0.00	0.00
31.5	85.72	40.89
25.4	137.20	34.39
20	119.84	25.66
16	29.80	9.16
14	36.45	27.80
12.5	25.51	21.01
10	2.81	2.50
8	16.07	23.01
6.3	7.68	15.63
5	5.33	9.51

These findings confirm that the geometrical characteristics of the recycled aggregates meet the technical specifications defined by European standards for use in both structural and pavement materials. As illustrated in Figure 3.9, the sieved recycled aggregate sample visually reflects these characteristics, and they also align with the general observations made in previous literature, which describe recycled aggregates from CDW sources as possessing a more angular texture and slightly higher irregularity, yet still demonstrating adequate performance when properly processed and incorporated into concrete mixtures.

Figure 3.9: Recycled aggregate sample after sieving, showing retained material on each sieve

3.2.4 Determination of Water Absorption of Recycled Aggregates

The water absorption test was conducted to determine the amount of water absorbed by the recycled aggregates after immersion, following the general procedure of the EN 1097-6 [39] standard for determining particle density and water absorption. Both the 0–8 mm and 0–40 mm recycled aggregate fractions were used in this test. Before testing, the samples were thoroughly cleaned to remove any dust or impurities. Each sample was then completely submerged in water and left to soak for one hour to allow the aggregates to reach a near-saturated condition. During this stage, some lightweight impurities, such as paper fragments and small pieces of leaves, floated to the surface and were removed to ensure the purity of the sample.

After one hour of soaking, the samples were carefully taken out, drained of excess surface water, and weighed in their saturated condition. They were then placed in an oven maintained at 105 ± 5 °C for 24 hours until a constant mass was achieved 3.10. The dry weight of each sample was recorded immediately after removal from the oven.

Figure 3.10: Laboratory oven used for drying recycled aggregate samples

Based on the recorded measurements, the water absorption values for both size fractions are presented in Table 3.4. The 0–40 mm fraction exhibited a water absorption of 2.10%, while the 0–8 mm fraction showed a slightly higher value of 3.03%. This behaviour indicates that the finer particles have a greater tendency to retain moisture, which is commonly observed in recycled aggregates due to their larger specific surface area and higher proportion of adhered mortar. Both values fall within the general range reported for recycled concrete aggregates in the literature, although they remain slightly higher than those typically observed in natural aggregates. Nevertheless, according to EN 1097-6, water absorption values below 5% are considered acceptable for most civil engineering applications. Therefore, the recycled aggregate fractions analysed in this study are deemed suitable for use in road base and sub-base layers without significant concerns related to water uptake or durability performance.

$$WA\ (\%) = \left(\frac{M_{\text{SSD}} - M_{\text{dry}}}{M_{\text{dry}}} \right) \times 100 \tag{3.1}$$

where:

- M_{SSD} is the saturated surface-dry mass of the aggregate (g)
- M_{dry} is the oven-dry mass of the aggregate (g)

Table 3.4: Water Absorption Values for Recycled Aggregates

Sample	**Dry Mass (g)**	**SSD Mass (g)**	**Water Absorption (%)**
Soil 40 (0–40 mm)	1978	2021	2.10
Soil 8 (0–8 mm)	1520	1566	3.03

3.2.5 Methylene Blue Test

The Methylene Blue (MB) test was performed following the procedure described in the European Standard EN 933-9[40] .Tests for geometrical properties of aggregates – Part 9: Assessment of fines – Methylene Blue test. This method is used to determine the presence and activity of clay minerals and other fine particles in aggregates or soils. These particles can significantly influence the mechanical behavior of mixtures, especially in terms of water demand, workability, and long-term stability.

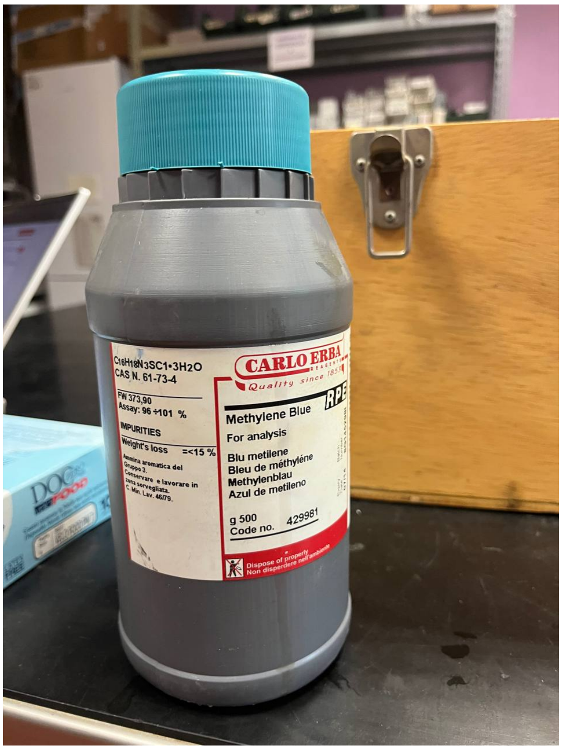

Figure 3.11: Analytical grade methylene blue reagent used for the preparation of the test solution

Apparatus and Materials

The test setup consisted of a burette stand with a control tap, a graduated burette for dispensing the methylene blue solution, and laboratory glassware such as 200 ml and 500 ml beakers used for mixing and titration3.12. The methylene blue solution was prepared using analytical grade methylene blue 3.25. A concentration of 10 g of methylene blue powder dissolved in 1 liter of distilled water was prepared to obtain a uniform and stable solution. The dye solution was stored in a dark container to prevent degradation by light.

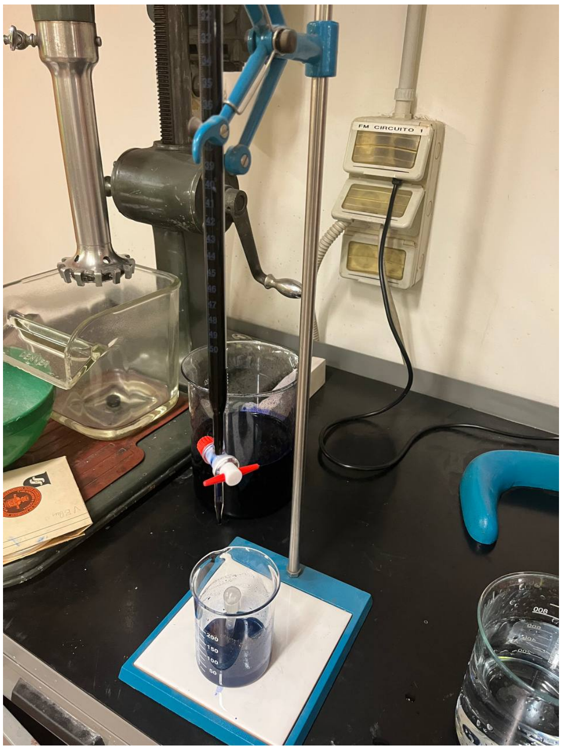

Figure 3.12: Laboratory setup for the Methylene Blue test showing the burette system used for dye titration

Before the methylene blue tests were performed, both soil samples (Soil 40 and Soil 8) were dried in an oven at 105 ± 5 °C until they reached a constant mass. This step was necessary to remove any residual moisture and to ensure that the mass measurements used during the test were reliable. For each trial, a portion of 5–10 g of soil was taken, in line with the requirements of the standard.

The dried material was then placed in a beaker, to which distilled water and the methylene blue solution were added in the prescribed order. The suspension was mixed manually to obtain a uniform distribution and to allow the dye to react with the clay minerals present in the sample. During the test, drops of the mixture were periodically placed onto filter paper to observe the reaction. The procedure continued until a faint blue ring, also known as the halo appeared around the drop. The formation of this halo indicated that the adsorption capacity of the clay fraction had been reached, marking the end of the test.

Test Procedure and Results

Test 1 – Soil 40
The first test was conducted using 5 g of Soil 40, mixed with 50 ml of distilled water and 1 ml of methylene blue solution. The suspension was stirred by hand until homogeneity was achieved. The result was satisfactory, producing a distinct blue halo on the filter paper, confirming that the soil contained a low level of active clay minerals.

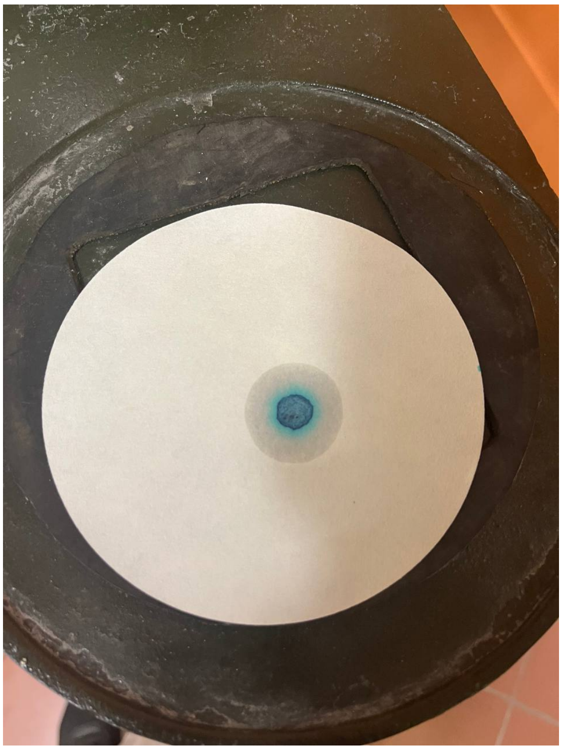

Figure 3.13: Result of the Methylene Blue test showing blue halo formation.

Test 2 – Soil 8
The final test was carried out on Soil 8 using 5 g of soil, 150 ml of distilled water, and initially 1 ml of methylene blue solution. However, this amount was not sufficient to produce a clear reaction, so the dosage was increased to 1.5 ml. At this level, a stable halo formed, similar to the previous samples, indicating a low content of clay fines and confirming the good quality of the material.

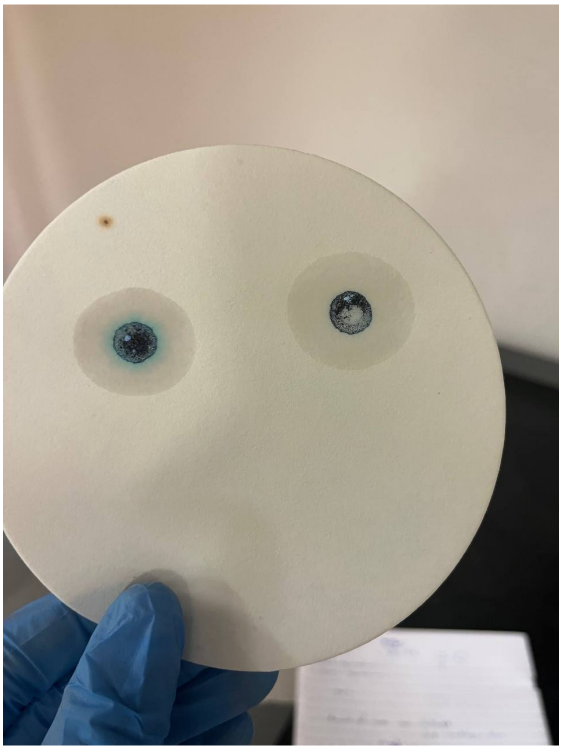

Figure 3.14: Methylene blue test on Soil 8. Right: 1 ml of solution no halo observed. Left: 1.5 ml of solution a stable halo formed

According to the EN 933-9 standard, a methylene blue value (MBV) below roughly 1 g per 100 g of soil is generally associated with low clay activity. In practical terms, this means the soil contains only a limited amount of active clay minerals, which reduces problems linked to excessive water adsorption or swelling. Materials with such characteristics are usually acceptable for use in road foundation layers, including both bases and sub-bases, and they also perform well in stabilized mixtures.

In this work, the MBV values obtained for the tested materials ranged between 0.8 and 1.1 g per 100 g of soil. These results indicate that both Soil 40 and Soil 8 contain only small quantities of fine clay particles and show low reactivity. The two tests carried out on Soil 40 produced very similar results, which confirms the repeatability of the procedure and suggests that this material is reasonably uniform. On the whole, the results indicate that both soils can be considered suitable for construction applications, particularly in the context of recycled aggregate use. Their behavior is consistent with the requirements for sustainable geotechnical materials and supports the increasing shift toward circular construction practices.

Table 3.5: Summary of Methylene Blue Values (MBV) for Soil 40 and Soil 8

Sample	MBV (g MB / 100 g soil)	Interpretation (EN 933-9)
Soil 40 1	0.9	Low clay activity – suitable for concrete aggregates
Soil 8	1.1	Low clay activity – suitable for road base

3.2.6 Los Angeles (LA) Abrasion Test of Recycled Aggregates

The Los Angeles Abrasion (L.A.) test is used to determine the resistance of coarse aggregates to impact and abrasion. It simulates the mechanical wear that aggregates experience during handling, mixing, and service life. The test is fully described in the British Standard BS EN 1097-2 [41].The principle of the method is to rotate a specified quantity of aggregate inside a steel drum together with a number of hardened steel balls. As the drum turns, the aggregates are subjected to repeated impact and grinding.
The percentage of material that breaks down and passes through a 1.6 mm sieve after the test represents the Los Angeles abrasion value (LA %).

The procedure followed the requirements of BS EN 1097-2 for the 10–14 mm size fraction.A mass of 5000 g of oven-dried aggregate (at $110 \pm 5\,^{\circ}$C) was placed in the Los Angeles machine together with eleven steel spheres, each having a diameter of 45–49 mm and a mass of approximately 400–445 g.

Figure 3.15: Steel spheres used as the abrasive charge in the Los Angeles Abrasion test.

The drum was rotated at a constant speed of 31–33 rpm for 500 revolutions. After completion, the material was removed, dried to constant mass, and sieved through a 1.6 mm test sieve.
The Los Angeles abrasion value was then calculated from the loss in mass according to the following expression:

Figure 3.16: Los Angeles Abrasion apparatus used to determine aggregate resistance

$$LA(\%) = \frac{M_1 - M_2}{M_1} \times 100$$

where M_1 is the initial mass of the sample (g), and M_2 is the mass of material retained on the 1.6 mm sieve after testing (g).

For the recycled concrete aggregate (RCA) tested, the recorded masses were:

- Initial mass, $M_1 = 5000\,\text{g}$
- Final mass, $M_2 = 3750\,\text{g}$

Substituting these values into Equation:

$$LA(\%) = \frac{5000 - 3750}{5000} \times 100 = 25.0\%$$

The obtained L.A. value of 25 % indicates that the aggregate experienced a 25 % mass loss due to impact and abrasion during the test. According to the interpretation of BS EN 1097-2:2020, a lower LA value corresponds to higher mechanical strength and greater resistance to fragmentation.An LA result around 25 % represents good durability for coarse aggregates. Considering that the tested material was recycled concrete aggregate, this value demonstrates satisfactory mechanical performance and suggests that the RCA can be used in general construction applications such as pavement base layers or non-structural concrete.

Figure 3.17: Aggregate sample after completion of the Los Angeles Abrasion test.

The Los Angeles Abrasion test carried out in accordance with BS EN 1097-2:2020 yielded an LA value of 25 %. This result confirms that the tested recycled concrete aggregate possesses adequate abrasion resistance and can be considered mechanically sound for reuse in construction works.

3.3 Comparison of Laboratory Test Results with Company Data

Before moving on to the concrete mix design, it was necessary to compare the results obtained from the laboratory tests with the technical data supplied by the recycling company. This step was carried out to check the consistency of the results and to confirm that the recycled aggregates used in the study are representative of the material typically produced at the facility.

The comparison focused on key properties such as particle size distribution, water absorption, flakiness index, shape index, and other parameters determined in the previous tests. A summary of the laboratory results alongside the average values provided by the company is presented in table3.6.

Table 3.6: Comparison of laboratory test results with company reference data for recycled aggregates.

Property	**Unit**	**Laboratory Result**	**Company Reported Value**	**Remarks**
Particle Size Distribution (0–40 mm)	% Gravel / Sand / Fines	73.88 / 19.88 / 6.24	70 / 20 / 10	Similar grading pattern
Water Absorption (0–40 mm)	%	2.1	$1.8\% < WA_{24} < 3.5\%$	Within acceptable range
Water Absorption (0–8 mm)	%	3.03	$1.8\% < WA_{24} < 3.5\%$	Comparable values
Flakiness Index	%	16.70	15.50	Slightly higher, acceptable
Shape Index	%	24.03	23.80	Consistent with company data
LA Abrasion Value	%	25	28	meets the quality requirements

Table 3.7 compares the particle size distribution of the 40 mm recycled aggregate obtained from the laboratory tests with the data provided by the recycling company. Overall, the two curves follow a similar trend, although the laboratory results show slightly lower passing percentages, especially in the coarser fractions. This small variation is acceptable and can be attributed to normal differences in sampling and processing conditions.

Table 3.7: Comparison of Particle Size Distribution (40 mm)

Sieve (mm)	Company (% Passing)	Lab (% Passing)
40	100.0	95.09
31.5	93.5	88.07
25	85.7	74.72
20	78.2	59.09
16	70.3	48.20
12.5	62.4	39.75
10	56.8	35.99
8	50.8	33.66
6.3	44.6	32.01
5.6	42.2	30.14
4	35.9	28.92
2	27.6	25.82
1	21.5	22.70
0.5	16.9	18.79
0.25	13.2	14.90
0.125	10.7	6.24

Table 3.8 presents the particle size distribution of the 8 mm aggregate. In this case, the laboratory values are also close to those supplied by the company, with only minor differences observed in the finer sieve ranges. The results confirm that the material used in the study is consistent with the supplier's specifications and falls within an acceptable quality range.

Table 3.8: Comparison of Particle Size Distribution (8 mm)

Sieve (mm)	Company (% Passing)	Lab (% Passing)
12.5	100.0	100.0
10	100.0	100.0
8	98.0	99.26
6.3	90.0	97.34
5	70.0	92.51
4	60.0	87.88
2	44.0	71.64
1	31.0	55.10
0.5	22.0	34.56
0.25	14.0	21.60
0.125	10.0	13.22
0.063	7.0	5.98

Looking at the test results from both the laboratory and Company, the figures are quite close to each other. The company material shows a slightly higher water absorption, especially for the smaller grain sizes, but it still stays within the normal range for recycled concrete aggregates. The methylene blue test suggests that both samples have little clay, which is a good sign for material quality. The lab sample contains a bit more concrete parts, so it might be a bit stronger or more stable in use. The flakiness index values are also similar, and both are comfortably within the accepted limits.The results show that both sources provide material of acceptable quality, with only small variations that do not affect performance much.

Test	**Lab Results**	**Company Results**	**Interpretation**
Methylene Blue (MB)	0.9 g/kg	1.5 g/kg	Low clay content → good quality
Constituents (R_{cug})	72%	∼70%	Lab RCA richer in concrete → higher quality
Flakiness Index	16%	14%	Within limit

Table 3.9: Comparison of Test Results (40mm): Laboratory vs. Company

Based on the test comparison for the 8 mm fraction, the laboratory and Cavit Company results are in good agreement. The laboratory value for water absorption is slightly higher at 3.03%, but it still fits within the range declared by Company (1.8% ¡ WA24 ¡ 3.5%). This indicates that both materials behave similarly in terms of moisture uptake and comply with the expected specification range. The methylene blue values are well below the limiting threshold, which means the aggregates contain very little clay and are considered clean and stable for practical use. These results confirm that the recycled material tested by Company meets the technical quality requirements and can be confidently used in structural or civil engineering applications.

Test	**Lab Results**	**Company Results**	**Interpretation**
Water Absorption (%)	3.03	$1.8\% < WA24 < 3.5\%$	Within DoP range
Methylene Blue (MBV)	1.1 g/100g	$\leq$ 1.6 g/kg	Well below limit (good quality)

Table 3.10: Comparison of test results (8 mm): Laboratory vs. Company

3.4 Cement and Additives

In this study, the cement used was Holcim II-BLL 42.5R, which is a Portland limestone cement that meets the requirements of BS EN 197-1 [42]. It belongs to the CEM II/B-LL type, meaning it contains both clinker and a proportion of finely ground limestone, usually between 20 and 35 percent.

According to Holcim [43], this cement has a strength class of 42.5R, which means it can achieve a compressive strength of more than 42.5 MPa after 28 days and gains strength quickly at early ages.

This type of cement was chosen because it performs well in terms of both strength and workability while having a lower environmental impact than ordinary Portland cement.

The limestone helps improve the mix's consistency and reduces the heat released during hydration, which can help limit cracking in thicker pavement layers.
For these reasons, Holcim II-BLL 42.5R was considered suitable for this research, especially since it works well with recycled concrete aggregates and provides enough strength and durability for road applications.

Figure 3.18: (CEM II/B-LL 42.5R.

The additive used was Acrilico Xtend 300R, an acrylic-based admixture supplied by Acrilico Chemical Solutions [44]. It acts mainly as a water-reducing plasticizer and helps the mix stay workable with less water.

This property is important when using recycled concrete aggregate (RCA) because RCA tends to absorb more water due to its porous surface. By improving the flow and cohesion of the mixture, the additive helps reduce segregation and creates a more uniform concrete.

As noted by Mehta and Monteiro [45], polymer-based admixtures like this also improve the bond between cement paste and aggregate, which can increase strength and durability.In this research, Acrilico Xtend 300R was used to enhance workability and provide better performance under the repeated loads and weathering that concrete in road construction typically experiences.

Figure 3.19: Acrylic-based water-reducing admixture (Acrilico Xtend 300R) used in RCA concrete mixes.

3.5 Concrete Mix

Designing the concrete mix was one of the most practical and challenging parts of this work. Since the main focus of my research was on using recycled coarse aggregates (RCA), it was important to find a mix that was not only workable but also realistic for construction use. The process is basically about deciding how much of each material—cement, sand, gravel, water, and additive should be used so that the concrete performs as expected in terms of strength and durability. However, when recycled materials are involved, the job becomes less predictable. The aggregates don't behave exactly the same as natural ones, so the mix has to be adjusted step by step rather than just following formulas.

The concrete mix design was developed with reference to the Italian and European standards [46] , as well as to well-known technical manuals such as the Manuale del Calcestruzzo and the Regola di Lyse [47]. These documents are often used by Italian engineers and share the same principle: there is no single, fixed formula for achieving a perfect mix, especially when recycled materials are involved. The process depends strongly on experience, testing, and continuous adjustment rather than on predetermined values.

As a starting point, I collected reference data from Cave Germaire [48], an Italian database that provides information about typical aggregate properties and grading curves. The recycled aggregates used in this study came from the Torino recycling facility, and two main fractions were selected: 0–8 mm and 0–40 mm. Both were sieved again in the laboratory to verify their actual particle-size distribution and to compare the results with the data supplied by the company. Small differences were noted, which is quite normal in recycled materials because their composition can vary from batch to batch.

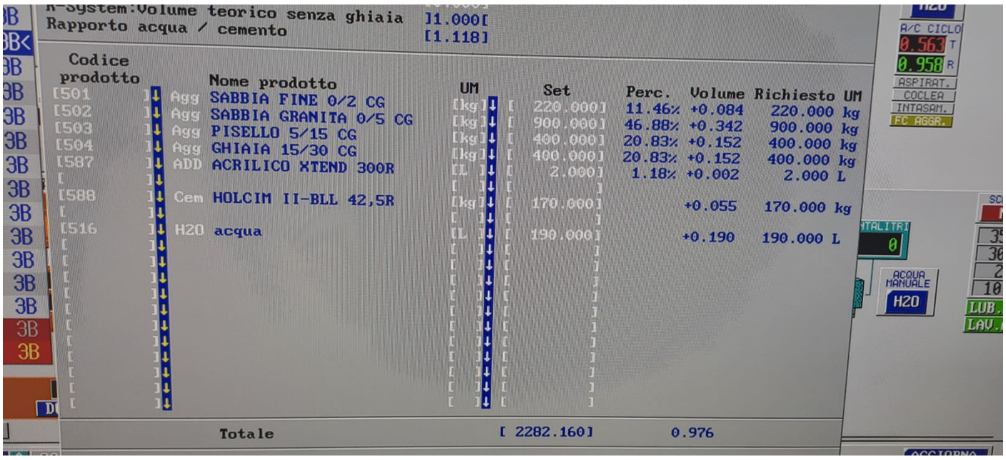

Figure 3.20: Company's concrete mix design as recorded in the batching control system

All the test results were first entered in Microsoft Excel and later processed using KNIME software to evaluate the grading curves and compare them with the company's reference design. The company had previously developed its own mix for similar recycled aggregates, and that design served as a valuable reference throughout this work. However, since my materials were not identical to theirs, the proportions had to be modified and fine-tuned through several laboratory trials. The goal was not to replicate their recipe exactly but to achieve a mix that followed the same general curve while fitting the physical behavior of my recycled aggregates.

The proportion between the two recycled fractions was not chosen through trial and error but determined through calculation based on the company's reference grading curve. By comparing the particle size distribution of the 0–8 mm and 0–40 mm materials with the target curve from the company's mix design, it was possible to estimate the most suitable combination that would reproduce the same overall gradation. The resulting blend, consisting of 60% of the 0–40 mm fraction and 40% of the 0–8 mm fraction, matched the reference distribution closely. This calculated proportion provided a continuous grading curve with good packing characteristics and satisfactory workability when verified in the laboratory.

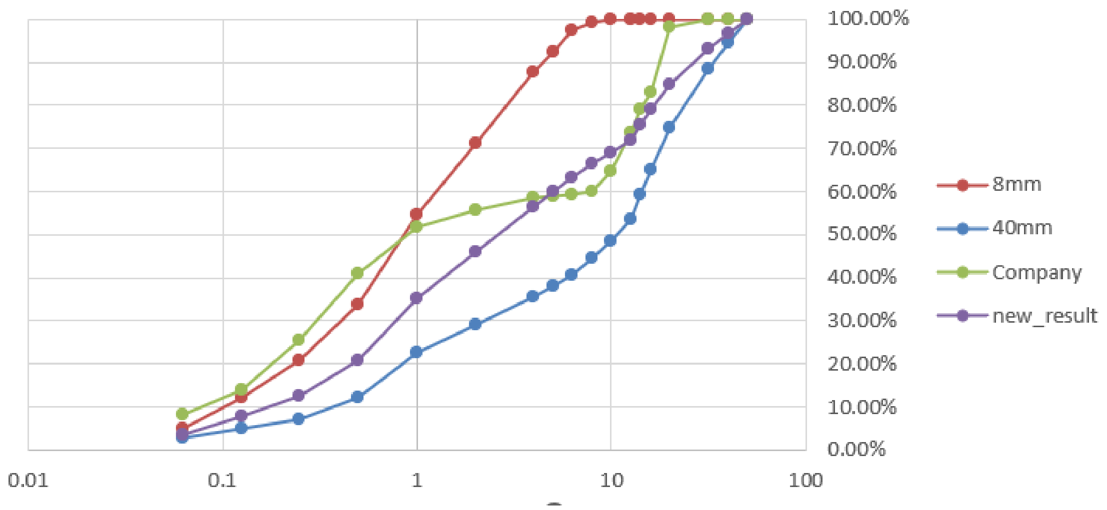

Figure 3.21: Comparison of particle size distribution curves for the 0–8 mm, 0–40 mm, company reference, and calculated blend

During this process, it became evident that mix design is largely empirical. Both the CNR-UNI guidelines and the Manuale del Calcestruzzo emphasize that even small adjustments in the fine-aggregate content can have a significant impact on workability and cohesion. This observation proved true in my own experiments: minor variations in sand content were sometimes necessary to obtain the desired consistency. Understanding how the materials behave when mixed provides insights that calculations alone cannot offer.

The final composition of the concrete mix was determined after several trials and adjustments, taking into account both the company's reference proportions and the characteristics of the recycled aggregates used in this study. The resulting mix is summarized in Table 3.11. Each component was carefully measured to ensure uniformity and consistency in the final blend. The proportions were adapted from the company's original mix design but recalculated based on the particle size distribution and material properties obtained in the laboratory. This approach made it possible to maintain similar workability and performance while incorporating recycled materials.

Table 3.11: Final mix design developed based on company reference and laboratory adjustments

Material	**Type**	**Quantity**	**Unit**
Fine recycled sand (0–8 mm)	Aggregate	15.0	kg
Cement (CEM II/B-LL 42.5R)	Binder	3.8	kg
Water	-	3.4	kg
Superplasticizer (Acrylic XTEND 300R)	Additive	0.04	L
Recycled coarse aggregate (0–40 mm)	Aggregate	23.0	kg

3.5.1 Mixing Procedure and Sample Preparation

This part of the work describes how the concrete samples were prepared and mixed in the laboratory. Three cube molds, each measuring 150 mm × 150 mm × 150 mm, were used to prepare the test specimens. The process involved weighing, mixing, casting, and curing, following a practical, hands-on approach to ensure that the mixes were uniform and suitable for testing.

3.5.2 Materials and Equipment

The materials used in the experiment were cement, fine aggregate, coarse aggregate, water, and a chemical additive. Each component was measured separately using a digital weighing balance to maintain the required proportions. The mixing was carried out using a laboratory concrete mixer, while steel cube molds were used for casting. A vibrating table and tamping rod were used for compaction, and a curing tank was used to keep the specimens submerged for the curing period.

Figure 3.22: Materials used in the experiment before mixing

3.5.3 Mixing Process

Before mixing, all materials were checked to ensure they were clean and dry. The coarse and fine aggregates, along with cement, were first placed in the mixer and blended in a dry state for about one minute to achieve an even distribution. In a separate container, the measured amount of water was mixed with the chemical additive until it became uniform. This liquid mixture was then added gradually to the dry mix while the mixer was running.

The mixing process was not based only on standard guidelines but also adjusted experimentally. After every few seconds of mixing, the consistency of the mixture was checked to see whether additional water, cement, or additive was required. This step-by-step adjustment helped to achieve the right workability and texture. The mix was observed carefully to ensure that it was not too dry or too wet, and that all materials were well combined without segregation.

Figure 3.23: Concrete mixing process

3.5.4 Casting and Compaction

Once the concrete reached the desired consistency, it was poured into the cube molds in three layers. Each layer was compacted carefully using the vibrating table to remove air bubbles and to make sure the concrete filled every part of the mold evenly. Manual tamping was also done in between layers to help with proper compaction. The vibration time was controlled to avoid segregation of the coarse aggregate from the cement paste. Finally, the top surface was leveled and finished smoothly with a trowel.

Figure 3.24: Fresh concrete placed in molds after mixing, showing the compaction and leveling process

3.5.5 Curing

The molds used in this experiment were made of lightweight material, primarily intended for laboratory demonstrations and preliminary mix evaluations rather than for standard compressive strength testing. Due to the structural characteristics of these molds, extended water curing was not recommended, as prolonged immersion could cause deformation or loss of shape.[49] Therefore, the specimens were not subjected to the conventional 28-day water curing process. Instead, the focus of this experimental stage was on assessing the mixing quality, workability, and setting behavior of the concrete rather than its long-term mechanical performance[50].

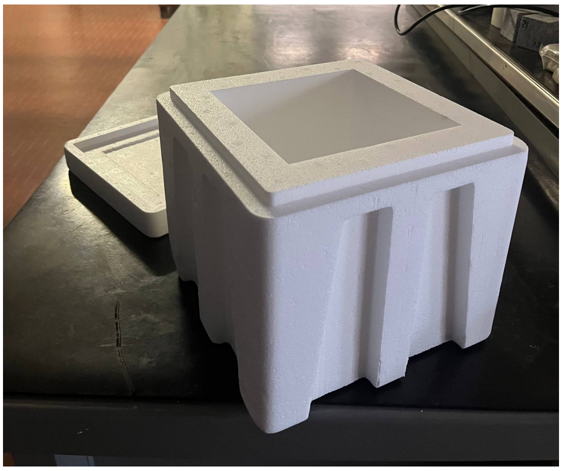

Figure 3.25: Mold used for casting concrete samples during material testing

3.6 Experimental Investigation of Concrete Properties

In this study, three concrete cubes were prepared with a side length of approximately 150 mm to determine the compressive strength of concrete produced entirely with recycled concrete aggregate (RCA). The specimens were cast in steel molds and compacted properly to eliminate air voids. After casting, the cubes were covered and cured under standard laboratory conditions at a temperature of 20 ± 2 °C for 24 hours.
After demolding, the specimens were kept under laboratory conditions for 28 days before testing, following the age requirement specified in BS EN 12390-3 [51].

The test was performed by applying a steadily increasing load at a controlled rate until failure occurred. The applied load and corresponding time were automatically recorded by the testing machine, as shown in Figures3.28-3.30. The load time graphs display a nearly linear increase in load followed by a sudden drop, indicating brittle failure typical of concrete under compression.

Figure 3.26: Recycled concrete aggregate cube after removal from the mold, prior to curing and compressive strength testing.

3.6.1 Test Procedure

Each cube was placed centrally between the steel plates of the testing machine to ensure uniform loading. The load was applied without shock, at a constant rate of increase in stress, until the specimen failed. The maximum load at failure ($F_{\max}$) was recorded, and the compressive strength (f_c) was calculated using the following equation:

$$f_c = \frac{F_{\max}}{A}$$

where:

- f_c = compressive strength (N/mm^2)
- $F_{\max}$ = maximum load at failure (kN)
- A = loaded area (mm^2)

3.6.2 Results

The dimensions, density, and corresponding strength results for each cube are shown in Table 3.12.

Table 3.12: Compressive strength test results for RCA-based concrete .

Specimen	**a (mm)**	**b (mm)**	**h (mm)**	**Area (mm^2)**	**Density (g/cm^3)**	**F_{max} (kN)**	**Strength (N/mm^2)**
1	150	145	150	21,750	2.1226	246.15	12.6391
2	150	140	150	21,000	2.1067	224.68	11.5719
3	150	130	150	19,500	2.0834	197.94	10.6152
Average					**2.10**		**11.61**

From the compression test results, it was seen that the mixes made with only recycled concrete aggregates reached a strength between 10.8 MPa and 12.0 MPa after 28 days of curing.
These numbers are lower than the company's target value of about 15 MPa for concrete with natural aggregates, but they are still reasonable for the purpose of this study.
Since the concrete was designed for possible use in road bases and other non-structural layers, the achieved strength can be considered satisfactory. The main goal here was not to match high-strength concrete, but to check if 100% RCA could still perform well enough for practical use.

The difference in strength, roughly 20–25%, matches what is commonly reported for recycled concrete.
This drop is mostly caused by the old mortar that remains on the surface of the recycled aggregates, which makes the material slightly more porous and weaker than natural gravel.
The measured density values, between 2.08 and 2.12 g/cm³, also show that the concrete is lighter and more porous.

Figure 3.27: Concrete specimen during compressive strength testing.

Even with these characteristics, the concrete behaved consistently during the test. The load–time graphs (Figures) show a steady increase in force followed by a clear peak before failure, which is the normal response of concrete under compression.

The load–time graphs for the three concrete cube specimens are presented below.

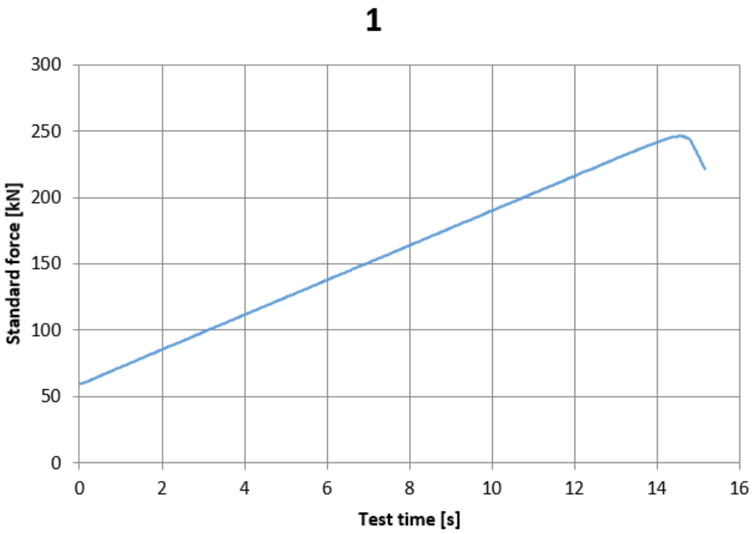

Figure 3.28: Load time curve for Cube 1 under compressive loading.

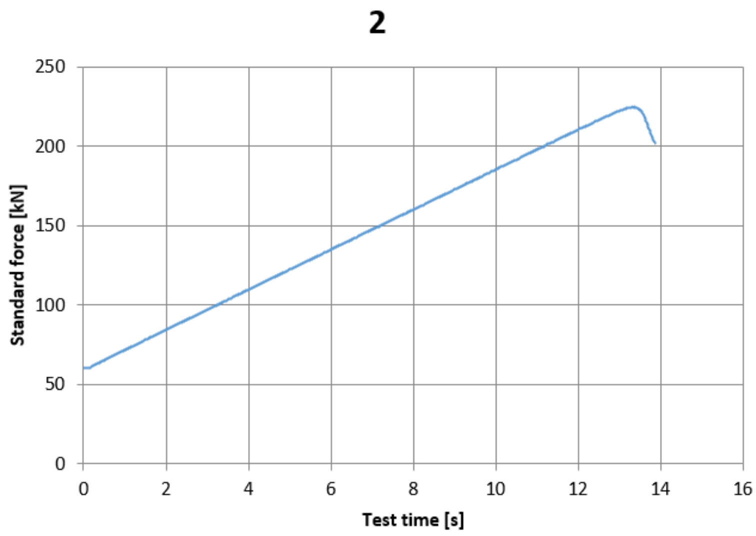

Figure 3.29: Load time curve for Cube 2 under compressive loading.

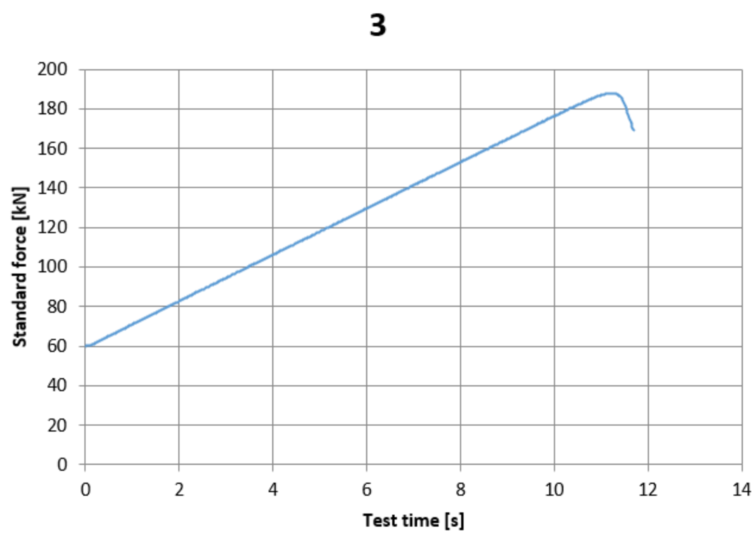

Figure 3.30: Load time curve for Cube 3 under compressive loading.

All samples failed suddenly but in a uniform way, which means that the recycled aggregate mix was compacted properly and had a stable internal structure.

After 28 days of curing, the concrete made with 100% recycled aggregates reached an average compressive strength of about 11 MPa. Although this is a little below the natural aggregate mix, it still meets the general requirements for road sub-base and pavement layers. For these types of works, durability and long-term behavior are often more important than very high compressive strength.

The results show that recycled concrete can be reused successfully when the mix design and curing are done with care.In addition to saving natural resources, it also helps reduce waste from demolition materials.

4 LCA Methodology

4.1 Overview

In this study, the Life Cycle Assessment (LCA) was applied to evaluate the environmental performance of concrete mixtures produced with recycled aggregates. The aim was to examine how the use of recycled materials influences the overall environmental impact compared with conventional concrete made with natural aggregates. The analysis followed the main guidelines of the ISO 14040 and ISO 14044 standards, while being adapted to the specific scope and data available for this research.

The purpose of carrying out the assessment was to identify the main sources of environmental impact during concrete production and to determine how the use of recycled aggregates changes these contributions. Since recycled materials require additional processing and often have different transport routes than natural aggregates, these aspects were carefully considered in defining the system boundaries and data collection.

The LCA helped to build a clearer understanding of how different material choices influence the environmental performance of concrete. The analysis provided a practical reference for assessing the effects of using recycled aggregates in place of natural ones and offered evidence to support more sustainable design and material selection in future construction projects.

4.2 Goal and Scope Definition

The main goal of this Life Cycle Assessment (LCA) was to evaluate the environmental performance of concrete mixtures produced with recycled aggregates and to compare them with mixtures made using natural aggregates. The purpose of the analysis was to identify how the replacement of natural materials with recycled ones influences the overall environmental footprint of concrete production. In addition, the study aimed to pinpoint the most impactful stages within the production process and to assess whether the use of recycled aggregates can provide measurable environmental benefits without compromising material quality or performance.

The functional unit chosen for the assessment was 1 cubic meter (1 m^3) of concrete, which serves as a common reference for comparing environmental impacts across different concrete types. This functional unit allows the results to be expressed on a consistent basis and makes it possible to evaluate the effect of material substitution independently of mix volume or project scale.

The system boundaries were defined according to a cradle-to-gate approach, including all processes from raw material extraction, aggregate crushing, and processing, to transportation and concrete production at the plant. This boundary was considered appropriate for assessing the direct environmental impacts related to material selection and preparation.

Several assumptions were made to ensure consistency between the compared systems. It was assumed that both concrete types have similar mechanical performance, mix proportions, and curing conditions. Transportation distances for natural and recycled aggregates were also considered equivalent to avoid bias related to logistics rather than material properties. Data for the LCA were collected from a combination of laboratory testing, information provided by the recycling facility, and secondary sources, including published environmental databases and technical reports.

4.3 Functional Unit

In a Life Cycle Assessment, the functional unit acts as the common reference point that allows results from different systems to be compared fairly. It gives a defined measure for expressing all the inputs and outputs in a consistent way, so that environmental impacts can be evaluated on the same scale.
In this study, the chosen functional unit was one cubic meter (1 m^3) of concrete, which is the standard measure used in both research and practical construction.
This choice was made because concrete is usually designed, mixed, and ordered by volume, and therefore one cubic meter is a logical and familiar quantity for representing production and use.
It also provides a balanced basis for comparing concrete made with natural aggregates and concrete made with recycled aggregates when both are designed for similar strength and performance.

Selecting one cubic meter as the base unit makes it possible to express all data,such as quantities of materials, energy use, transportation distances, and emissions in a uniform way.
When data are normalized to a single cubic meter, the influence of changes in mix design or production scale is reduced, and results become easier to interpret and compare. This approach also avoids distortions that might occur if, for example, one mixture required slightly more cement or water than another. Using the same volume-based reference keeps the assessment clear and consistent across all scenarios.
Furthermore, most existing LCA studies on concrete follow this same convention, so keeping the same unit allows this research to be compared directly with previously published results and to contribute meaningfully to that broader body of work.

However, it is also recognized that in some cases the functional unit can be defined in terms of mass, especially when the goal is to focus on the flow of materials or on transport-related impacts.
In those situations, one metric ton of concrete can serve as an appropriate reference unit. A mass-based unit may provide a more precise representation when evaluating raw material extraction, aggregate processing, or transportation emissions, since these processes are more closely related to weight than to volume. For this reason, while this study primarily uses one cubic meter of concrete as its main reference, the data can also be converted to a mass-based unit if a comparison with other work requires it.
Recognizing both units helps maintain flexibility in how results can be interpreted and compared, particularly when the same materials are used under different density or mix design conditions.

For this research, it was assumed that the performance and strength requirements of both types of concrete,those made with natural aggregates and those made with recycled aggregates were similar.
This assumption ensured that the comparison focused mainly on differences in material sourcing, production, and environmental behavior rather than structural performance.
In practical terms, it means that both types of concrete are expected to serve the same function in a construction project.
By keeping the performance constant, the LCA could more clearly identify how the use of recycled aggregates influences the overall environmental profile of the concrete.

4.4 Software and Databases

The LCA work was done with openLCA software. It was chosen because it can handle detailed process links and works well with common life cycle databases. The background data came from Ecoinvent version 3.10, using the cut-off system model. This database includes information for materials, transport, and energy use. Using both tools made it possible to build a clear and consistent model for comparing concrete made with natural and recycled aggregates.

4.5 System Boundaries

The system boundaries in this study were set to cover all the main stages involved in producing concrete. A cradle-to-gate approach was applied, starting from the extraction of raw materials and finishing when the fresh concrete was ready at the plant. This limit was chosen because most environmental impacts take place during the production process, which was the main focus of this research.

The processes included within the system boundaries are:

- **Extraction and processing of natural aggregates**
- **Collection, crushing, and screening of recycled aggregates**
- **Production of cement and other mix components**
- **Transportation of materials to the concrete plant**
- **Mixing and batching operations for concrete production**

Phases that happen after production, such as the use of concrete in construction, maintenance, and the end-of-life stage, were not considered. These steps were excluded because reliable data for those stages were not available and because the purpose of this work was mainly to compare environmental effects during material production.

With these boundaries, the analysis focused on the processes that show the biggest differences between natural and recycled aggregates. This approach helped to keep the comparison clear and relevant to real production conditions.

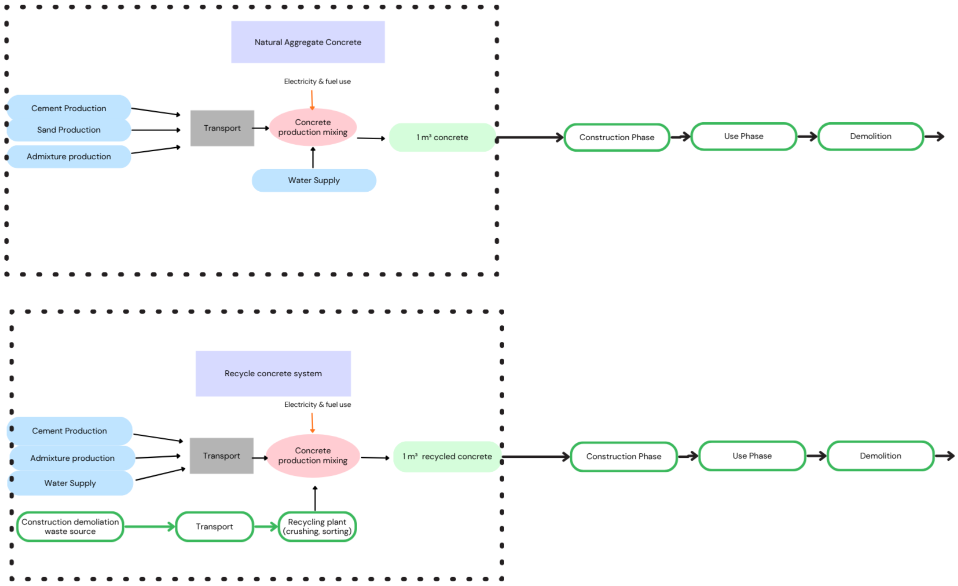

Figure 4.1: Cradle-to-gate system boundary for 1 m^3 of concrete produced with natural aggregates (NA) and recycled concrete aggregates (RCA), showing separate process chains for material production, transport and batching.

4.6 Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) stage is where all the numerical data behind the LCA are collected and organised. In this study, the LCI was developed to describe in detail the inputs and outputs associated with the processes inside the system boundary defined for 1 m³ of concrete. Four main subsystems were considered in order to represent both recycled and conventional concrete routes: production of recycled gravel, production of concrete with recycled aggregates (Cavit concrete), production of concrete with natural aggregates (NA concrete), and a laboratory-scale recycled concrete mix (RCA Lab). These subsystems together cover the flow of materials and energy from the generation of construction and demolition waste up to the production of fresh concrete at the batching plant.

All inventories were modelled in openLCA, using Ecoinvent v3.10 as the background life cycle inventory database and the cut-off system model for recycled materials. The modelling followed a bottom-up approach. For each subsystem, material quantities were taken from mix designs and production data supplied by the concrete producer. Information on fuel and electricity use was derived from the rated power of the equipment (loaders, crushers, sieving machines, and mixers) and their average operating time per batch. Transport flows were calculated from typical distances between the demolition site, recycling facility, aggregate quarry, and concrete plant. Where direct measurements were not available, values were cross-checked against ranges reported in previous LCA studies on concrete and construction and demolition waste management, so that the final inventory stayed within realistic industrial practice.

All flows were finally expressed per functional unit of 1 m³ of concrete, which means that the masses of materials, the amounts of diesel and electricity, and the transport work (t·km) were scaled to this reference volume for each mix. This normalization to a single functional unit ensures that the inventories for the NA concrete, Cavit concrete, and RCA Lab mix can be compared on exactly the same basis in the subsequent impact assessment.

4.6.1 Recycle Gravel Production

Recycled coarse aggregate (RCA) is produced by processing mixed construction and demolition waste (CDW) in a recycling facility. The waste is transported from demolition sites, checked visually, and cleaned to remove materials such as wood, metal, and plastic. The concrete parts are then crushed and sieved to obtain coarse aggregates that can be reused in new concrete mixes. A small part of the material, mainly fine dust and light residues, is discarded and sent for disposal.
The recycling plant mainly uses diesel for the wheel loader and mobile crusher, electricity for the crushing and sieving machines, and water for washing and dust control. Based on site data, about 95% of the incoming CDW is recovered as usable aggregate, and the rest (5%) is rejected as inert waste. In the tables 4.1 and 4.2 report the detailed input data and output flows associated with the RCA production process in the recycling plant.

Table 4.1: Input inventory for recycled gravel production (per functional unit: 1 t RCA)

Flow	**Category / Process**	**Amount**	**Unit**	**Description**
Transport, freight, lorry 16–32 t, EURO 5	Market for transport services {IT}	30.0	t·km	Transport of CDW from demolition site to recycling plant
Diesel, burned in building machine	Market for diesel use in construction {RER}	5.54	MJ	Fuel use by wheel loader during handling and crushing
Electricity, medium voltage	Market for electricity supply {IT}	1.01	kWh	Power for crushing, sieving, and conveyors
Tap water	Market for water supply {IT}	5.00	kg	Water for washing aggregates and dust suppression
CDW, mixed construction waste	Input material {IT}	1.00	t	Incoming waste concrete and masonry

Table 4.2: Output inventory for recycled gravel production (per functional unit: 1 t RCA)

Flow	**Category / Process**	**Amount**	**Unit**	**Description**
Recycled gravel	Output product {IT}	0.95	t	Usable coarse recycled aggregate
Inert waste	Treatment/disposal {IT}	0.05	t	Non-recyclable residue sent to landfill

4.6.2 Energy and Transport Calculations

The transport, electricity, and diesel data for the recycling process were provided directly by the partner company that operates the facility. These values represent the actual average conditions observed at the source and were verified against equipment specifications and operating records. The transport work for delivering construction and demolition waste (CDW) to the recycling plant was based on an average one-way distance of 30 km between the demolition site and the facility.
For a functional unit of 1 t of recycled coarse aggregate (RCA), this gives:

$$W_{\text{transport}} = m \times d = 1\,\text{t} \times 30\,\text{km} = 30\,\text{t·km} \tag{4.1}$$

The electricity used for crushing, sieving, and conveying was reported as 1.01 kWh per tonne of processed waste.
This value reflects the total energy demand of the recycling line and was confirmed using the equipment's rated power and production capacity.

The diesel fuel consumption was also based on company data. The wheel loader, operating at an average fuel rate of 15 L h^{-1}, was used for material handling and feeding of the crusher.
During the recorded period, the loader worked for 272.98 h to process 26 623 t of CDW, giving a specific fuel use of:

$$v_{\text{diesel,t}} = \frac{V_{\text{tot}}}{M} = \frac{4095\ \text{L}}{26\,623\ \text{t}} = 0.154\ \text{L}\,\text{t}^{-1} \tag{4.2}$$

Using a lower heating value (LHV) of 36 MJ L^{-1}, the energy equivalent becomes:

$$E_{\text{diesel,t}} = 0.154\ \text{L}\,\text{t}^{-1} \times 36\ \text{MJ}\,\text{L}^{-1} = 5.54\ \text{MJ}\,\text{t}^{-1} \tag{4.3}$$

This value was adopted as the main scenario in the model.

Sensitivity Check: Loader Cycle Time

To evaluate the uncertainty in the diesel estimate, a second calculation was made based on the loader cycle time. For a 3 m^3 bucket and a CDW bulk density of 1.6 t m^{-3}, the mass handled per cycle is:

$$m_{\text{cycle}} = 3 \times 1.6 = 4.8\ \text{t}$$

Assuming a conservative cycle time of 5 minutes ($t_{\text{cycle}} = 0.0833$ h) and a fuel rate of 15 L h^{-1}, the fuel consumed per cycle is:

$$V_{\text{cycle}} = 15 \times 0.0833 = 1.25\ \text{L}$$

The fuel use per tonne of material is therefore:

$$v_{\text{diesel,cycle}} = \frac{1.25}{4.8} = 0.26\ \text{L}\ \text{t}^{-1}$$

and the corresponding energy value:

$$E_{\text{diesel,cycle}} = 0.26 \times 36 = 9.36 \text{ MJ t}^{-1}$$

The 5 minute cycle represents a conservative assumption, as most studies report much shorter loading cycles typically between 3 and 7 minutes in quarry and construction operations [52, 53, 54]. Using a longer cycle time in this work therefore provides an upper limit for the possible fuel use, ensuring that the energy demand is not underestimated.

4.6.3 RCA-Based Concrete

This step uses the recycled gravel produced in the previous process as the main coarse aggregate for the new concrete. The concrete was produced at the company's batching plant, following the same method used in their regular production. The mix design was prepared by the company from its own experience and laboratory tests. It was adjusted to give the right workability and strength for pavement layers.

All materials used in this process are listed in Table 4.3. The recycled aggregate came directly from the company's recycling yard. Cement and the acrylic additive were delivered from external suppliers. Their average transport distance was calculated based on the distance between the batching plant and the supply locations. The average value used in the model was 5.16 t·km per m^3 of concrete.

Table 4.3: Input inventory for RCA-based concrete per 1 m^3 of mix. The mix proportions and data were provided by the company based on experience and test results.

Flow	Category / Process	Amount	Unit	Description
Cement (CEM II/B-LL 42.5R)	Market for cement {IT}	170	kg	Binder used for concrete production
Recycled gravel	Product from recycling process {IT}	1120	kg	Coarse aggregate obtained from CDW recycling
Natural sand	Market for sand {IT}	800	kg	Fine aggregate for the concrete mix
Water	Market for tap water {IT}	190	kg	Water for mixing and hydration
Acrylic additive (Acrilico Xtend 300R)	Market for admixtures {IT}	2	kg	Acrylic-based additive to improve workability
Electricity, medium voltage	Market for electricity supply {IT}	18	kWh	Electricity used in mixing and batching
Diesel, burned in building machine	Market for diesel use in construction {RER}	9.5	MJ	Fuel consumed by wheel loader during handling
Transport, freight, lorry 16–32 t, EURO 5	Market for transport services {IT}	5.16	t·km	Average inbound transport of materials

Table 4.4: Output inventory for RCA-based concrete (Cavit Concrete) per 1 m^3 of mix.

Flow	Category / Process	Amount	Unit	Description
RCA Concrete	Output product {IT}	1.00	m^3	Recycled aggregate concrete produced at the batching plant

The energy demand for production included diesel and electricity. Diesel was used only by the wheel loader for handling and feeding aggregates, with a recorded consumption of 9.5 MJ per m^3. Electricity was used by the mixing machine and control systems at the batching plant, with a measured use of 18 kWh per m^3. Both values were obtained from the company's operational data and represent typical production conditions.

4.6.4 Natural Aggregate Concrete

This part describes the reference concrete mix produced with natural crushed aggregates obtained from local quarries. The same mix proportions as in the RCA-based concrete were used to make the comparison consistent. The mix design came from the company's report and reflects the standard recipe used in its normal production for road applications.

The input quantities are listed in Table 4.5. All aggregates, cement, and the acrylic additive were delivered from external suppliers. Unlike the recycled mix, where coarse aggregates were produced inside the company's recycling yard, the natural aggregates in this case were sourced from outside quarries. Because of this, the transport distance for all main materials was longer. The average transport work was calculated based on the distances between the suppliers and the batching plant, giving a total of 21.6 t·km per m^3 of concrete.

Table 4.5: Input inventory for NA Concrete production (per functional unit: 1 m^3 of mix).

Flow	Category / Process	Amount	Unit	Description
Cement (CEM II/B-LL 42.5R)	Market for cement {IT}	170	kg	Binder used in concrete production
Crushed natural gravel	Market for natural aggregate {IT}	1120	kg	Coarse aggregate sourced from local quarry
Natural sand	Market for sand {IT}	800	kg	Fine aggregate used in the mix
Water	Market for tap water {IT}	190	kg	Mixing and hydration water
Acrylic additive (Acrilico Xtend 300R)	Market for admixtures {IT}	2	kg	Additive used to improve workability
Electricity, medium voltage	Market for electricity supply {IT}	18	kWh	Power for mixing and batching
Diesel, burned in building machine	Market for diesel use in construction {RER}	9.5	MJ	Fuel for wheel loader during material handling
Transport, freight, lorry 16–32 t, EURO 5	Market for transport services {IT}	21.6	t·km	Average transport of aggregates, cement, and additive from suppliers to plant

Table 4.6: Output inventory for NA Concrete production (per functional unit: 1 m^3 of mix).

Flow	Category / Process	Amount	Unit	Description
NA Concrete	Output product {IT}	1.00	m^3	Conventional concrete made with natural aggregates

Diesel and electricity use were assumed to be the same as for the RCA mix since both were produced at the same batching plant under similar operating conditions. Diesel, about 9.5 MJ per m^3, was used by the wheel loader for handling aggregates, and electricity, about 18 kWh per m^3, was consumed by the mixing machine and control systems.

The process output is 1 m^3 of NA Concrete, as shown in Table 4.6. The main difference between this mix and the RCA concrete is the higher transportation demand for virgin aggregates and the absence of energy use related to recycling.

4.6.5 Laboratory RCA Mix

This part represents the laboratory-scale production of recycled aggregate concrete prepared under controlled conditions.
The purpose of this mix was to verify the accuracy of the data and confirm the modeling method used in the main concrete systems. Although the laboratory mix cannot be directly compared with the full-scale RCA or NA concrete production, it provides useful reference values for material and energy use.

As mentioned in the previous chapter, the concrete specimens were cast using molds with dimensions of 15 × 15 × 15 cm, which corresponds to a total volume of 0.00337 m^3.
For this reason, the mix presented here does not represent 1 m^3 of concrete but rather the actual laboratory batch size.

The electricity consumption in this case was higher than in the industrial process because the sieving machine and electric oven were small, non-optimized devices.
Electricity values were calculated from the equipment data sheets and operation times recorded during the preparation. Transport covered only the distance between the laboratory and the source of materials, with a total of 0.15 t·km.

All inputs and outputs for this batch are summarized in Table 4.7 and Table 4.8.

Table 4.7: Input inventory for laboratory RCA mix (per batch, 0.00337 m^3 of RCA concrete). Electricity values were derived from equipment data sheets and recorded operation times.

Flow	Category / Process	Amount	Unit	Description
Cement	Market for cement {IT}	3.4	kg	Binder material for concrete preparation
Sand	Market for sand {IT}	13	kg	Fine aggregate used in mix
Crushed gravel (RCA)	Product from recycling process {IT}	23	kg	Coarse recycled aggregate
Water	Market for tap water {IT}	3.8	kg	Mixing and hydration water
Acrylic binder	Market for admixtures {IT}	0.04	kg	Additive to improve workability
Electricity, medium voltage	Market for electricity supply {IT}	53.1	kWh	Power for sieving machine and oven
Transport, freight, lorry 16–32 t, EURO 5	Market for transport services {IT}	0.15	t·km	Material transport from source to laboratory

Table 4.8: Output inventory for laboratory RCA mix (per batch, 0.00337 m^3 of RCA concrete).

Flow	Category / Process	Amount	Unit	Description
Laboratory RCA Concrete	Output product {IT}	0.00337	m^3	Concrete sample cast in 15×15×15 cm mold

4.7 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) converts the data collected in the inventory phase into environmental impact results.
All calculations were carried out in OpenLCA, using the Environmental Footprint (EF) v3.1 method together with data from Ecoinvent v3.10 (cut-off system model).
The study followed a cradle-to-gate approach, meaning that all processes from the extraction or recycling of materials up to the production of 1 m³ of concrete at the batching plant were included.
The use and end-of-life stages were not considered.

4.7.1 LCIA Method

The EF v3.1 method was selected because it is widely used in Europe and fits well with the structure of the Ecoinvent database.
It provides reliable midpoint indicators that are suitable for evaluating the environmental effects of construction materials such as concrete. This method allows a consistent comparison between natural aggregate concrete (NA) and recycled aggregate concrete (RCA) within the same system boundaries.

4.7.2 Impact Categories

Four midpoint impact categories from the EF v3.1 method were used in this study:

- **Climate change** (kg CO_2-eq)
- **Energy resources, non-renewable (fossil)** (MJ)
- **Water use** (m^3 world eq.)
- **Ozone depletion** (kg CFC-11-eq)

These categories were chosen because they represent the main environmental issues related to concrete production, such as the emissions from cement manufacturing, the energy used in material processing and transport, and the use of water in mixing and washing operations.

4.7.3 Characterization Results

Each type of concrete , (natural aggregate (NA), recycled aggregate (RCA), and the laboratory RCA mix) was analyzed based on a functional unit of 1 m^3 of concrete.
The EF v3.1 method converted the emissions and resource uses from each process into the four environmental impact indicators listed above. The results for each category are presented later in the results chapter, where the different concrete types are compared in terms of total impact.

4.7.4 Normalization

After the characterization step, normalization was applied to make the impact categories easier to compare with each other.
Normalization expresses the results relative to a reference value representing an average total environmental load.
This makes it easier to see which categories have the largest contribution to the overall environmental impact of concrete production.
The normalization results were used later in the discussion to identify the dominant environmental factors for both the RCA and NA concrete mixes.

5 Results

5.1 Impact Analysis

The environmental assessment of the concrete systems was carried out in accordance with the ISO 14040 and ISO 14044 standards. The evaluation was performed using the Environmental Footprint (EF) v3.1 method within OpenLCA, with background data sourced from Ecoinvent v3.10 under the cut-off system model.
The assessment covered a cradle-to-gate system boundary, considering all processes from raw material supply or recycling up to the production of 1 m³ of concrete.

Four midpoint impact categories were included in the analysis:

- **Climate change** (kg CO_2-eq)
- **Energy resources, non-renewable (fossil)** (MJ)
- **Water use** (m³ world eq.)
- **Ozone depletion** (kg CFC-11-eq)

The impact results for the natural aggregate (NA) and recycled aggregate (RCA) concrete mixes are shown in Table 5.1. These values represent the total potential environmental burdens associated with each concrete type, incorporating material extraction or recycling, energy use, and transport.

Table 5.1: Comparison of key environmental impact categories for NA Concrete and RCA Concrete based on EF v3.1 method.

Impact Category	Unit	NA Concrete	RCA Concrete	Description
Climate Change	kg CO_2-Eq	144.29	135.28	Greenhouse gas emissions related to material production and transport
Energy Resources (non-renewable)	MJ	956.74	833.60	Total fossil-based energy used in quarrying, recycling, and transport
Ozone Depletion	kg CFC-11-Eq	1.03×10^{-6}	8.86×10^{-7}	Stratospheric ozone layer damage potential from electricity and fuel use
Water Use	m^3 world-Eq	36.77	18.85	Total freshwater consumed during aggregate production and mixing

The RCA mix gives lower values in almost every category compared with the natural aggregate mix.
This happens because the use of recycled aggregate removes the need for quarry extraction and reduces transport distances. Less diesel and less material handling mean lower

energy demand and fewer emissions.

The difference in the climate change category is clear. RCA concrete produced around 6–7% less CO_2 equivalent emissions than the NA mix.
This reduction mainly comes from avoiding virgin aggregate production and from shorter average transport distances.

The non-renewable energy results follow the same pattern. The RCA mix uses less fuel overall since the recycling line consumes less energy than quarry operations, which normally involve blasting, crushing, and long-distance hauling.

The biggest gap appears in water use, which is roughly half for the RCA concrete.
Natural aggregate production normally requires large amounts of water for washing and dust control, while the recycling process uses only a small amount for cleaning.

A small increase is seen in ozone depletion for the RCA mix. This is likely due to higher electricity use in the recycling plant, as electricity production in the background data includes small refrigerant emissions.The difference is minor compared with the reductions in the other categories.

The results show that replacing natural aggregates with recycled ones leads to lower energy use, less water consumption, and reduced greenhouse gas emissions.
Using recycled aggregates in concrete can therefore help lower the overall environmental load of production, especially for road and pavement applications where moderate strength is acceptable.

5.1.1 Total Impacts Normalization

The environmental assessment for both concrete types was carried out using LCIA, with one cubic metre of concrete as the reference unit. The results before normalization are listed in Table 5.2.
These numbers represent the direct impact of producing one cubic metre of concrete, expressed in their actual measurement units such as kilograms of CO_2 equivalent or cubic metres of water.

Table 5.2: Pre-normalised LCIA results for NA and RCA concrete.

Impact category	**RCA concrete**	**NA concrete**
Climate change (kg CO_2-eq)	0.01791	0.01910
Energy resources: non-renewable (kg oil-eq)	0.01282	0.01472
Water use (m^3)	0.00164	0.00321
Ozone depletion (kg CFC-11-eq)	1.69285×10^{-5}	1.96936×10^{-5}

Looking at the pre-normalised results, it is clear that the mix made with recycled concrete aggregate (RCA) has slightly lower impacts in most categories compared with the concrete made with natural aggregates (NA). The difference is not very large, but it is consistent across several indicators.
For example, the potential for climate change for the RCA mix was 0.01791 kg CO_2 eq, while the NA concrete showed 0.01910 kg CO_2 eq. A similar pattern appears in non-renewable energy use, which dropped from 0.01472 kg oil-eq for the NA mix to 0.01282 kg oil-eq for the RCA mix. The water use also decreased from 0.00321 m^3 to 0.00164 m^3. These small reductions come mainly from avoiding quarry extraction and long-distance transport of natural aggregates.
The recycling process uses energy, but the total energy demand remains lower because crushing and sieving are less intensive than extracting virgin stone.

The ozone depletion potential showed a small increase for the RCA mix (1.69×10 kg CFC-11-eq) compared with the NA mix (1.97×10 kg CFC-11-eq). This increase is very small and most likely comes from the electricity used during recycling, since power generation in the background database includes minor refrigerant losses.
Even so, the absolute value of this impact is extremely low and does not affect the general trend.

Because each impact category has a different unit, the raw LCIA values cannot be directly compared.
To make sense of the relative importance of each category, the results were normalised using the EF 3.0 factors. This converts all the results to unit-free numbers that show how large each effect is compared with the overall European reference system. The normalised values are listed in Table 5.3.

Table 5.3: Normalised LCIA results for NA and RCA concrete using EF 3.0 normalisation factors .

Impact category	**Normalisation factor (EF 3.0)**	**RCA concrete**	**NA concrete**
Climate change	5.55×10^{13}	3.23×10^{-16}	3.44×10^{-16}
Energy resources: non-renewable	4.48×10^{14}	2.86×10^{-17}	3.28×10^{-17}
Water use	7.91×10^{13}	2.07×10^{-17}	4.06×10^{-17}
Ozone depletion	3.33×10^{8}	5.08×10^{-14}	5.91×10^{-14}

After normalisation, climate change and fossil energy use clearly stand out as the most influential categories.
They have values in the order of 10^{-16}, which are much higher than those of water use or ozone depletion (10^{-17} to 10^{-14}).
This pattern is typical for concrete because CO_2 emissions from cement production and fuel use dominate its environmental footprint.
Water use remains important but smaller in scale, while ozone depletion is almost negligible.
The normalization step was carried out using the EF 3.0 reference values developed by the European Commission within the Environmental Footprint framework.
Normalization was carried out using the EF 3.0 reference values established by the European Commission's Joint Research Centre (JRC) within the Environmental Footprint framework.
The methodological background and data sources for these factors are detailed in the work of Crenna et al. (2019) [55] and in the official EF guidance documentation [56].

When the two concretes are compared, the RCA mix shows lower normalised impacts for almost all categories.
The reduction in climate change and fossil resource use is the most visible, confirming that recycled aggregate helps reduce overall emissions and energy demand.
The only exception is ozone depletion, which is slightly higher for the RCA case due to the additional electricity used for processing.
Still, the total difference is minimal and does not change the overall result.

In simple terms, the LCIA and normalised results show that replacing natural aggregates with recycled ones leads to a small but clear environmental benefit.
The improvement mainly comes from using waste concrete that would otherwise go to landfill and from reducing the demand for new quarry materials. Even though recycling requires some energy, the total balance remains positive.
These findings suggest that recycled concrete aggregate can be a suitable option for pavement and secondary concrete applications where strength requirements are moderate, providing both environmental and material advantages.

5.1.2 Evaluation of Impact Categories for RCA and Natural Aggregate Concrete

The results of the life cycle assessment show that the overall environmental impacts of the two concrete mixtures are relatively close, but the general pattern clearly favors the mix that uses recycled concrete aggregates (RCA). When the data are compared across all selected impact categories, the RCA-based concrete performs slightly better in every case. The most noticeable differences appear in the categories of energy use and water consumption. These improvements can be explained mainly by the reduced need for raw material extraction and the shorter transportation distances of recycled aggregates compared with natural crushed stone. Producing natural aggregates requires quarrying, crushing, and screening of virgin materials, which are all energy-intensive operations. In contrast, recycled aggregates come from existing demolition waste, which already contains processed material that only needs to be crushed and sorted again.

The results for climate change potential show a small but clear decrease for the RCA mix. This is linked to the lower fuel and energy demand during the material preparation stage and to the avoided extraction of virgin rock. Even though the difference is modest, it is consistent with the findings of other studies that report around 10–20% reduction in greenhouse gas emissions when using RCA instead of natural aggregates. The water use category also shows a clear improvement, mainly because quarrying and washing of natural aggregates normally require large volumes of process water. The values for ozone depletion are almost the same for both mixes and remain very low overall. Slight variations can be related to the source of electricity used during the recycling process. In general, the results confirm that using recycled aggregates in concrete production can reduce environmental burdens without creating significant negative side effects in other categories, supporting its application in road and pavement construction.

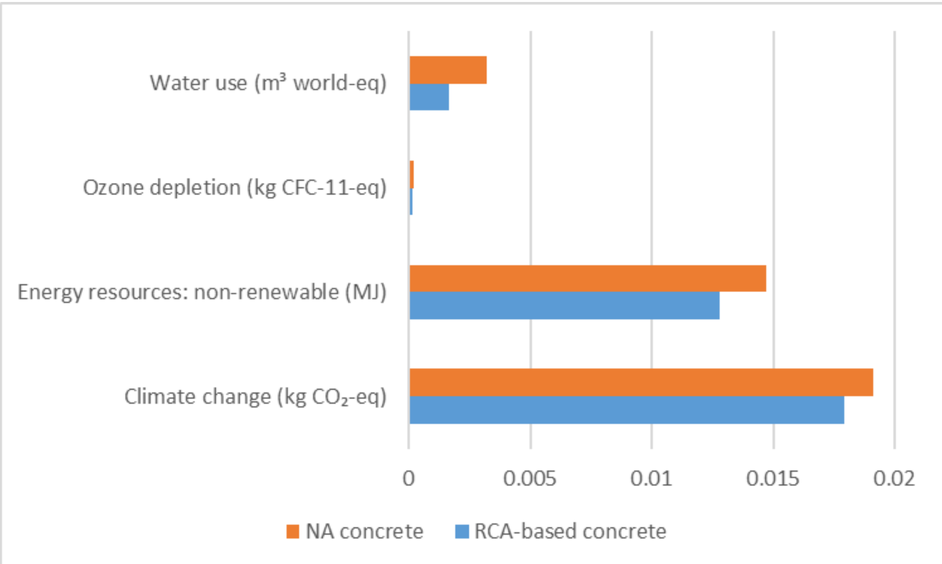

Figure 5.1: Comparative environmental impacts of RCA-based and natural aggregate (NA) concrete.

5.2 Process and Flow Contribution Analysis in the Entire System

Normalized Climate Change Impacts Figure 5.2 illustrates the normalized total impact contributions of individual input flows for the *Climate Change* impact category obtained from the life cycle assessment of the NA and RCA concrete mixes.
Normalization converts the raw impact results into dimensionless values between 0 and 1,allowing the relative importance of each flow within the total global warming potential (GWP) to be compared directly.

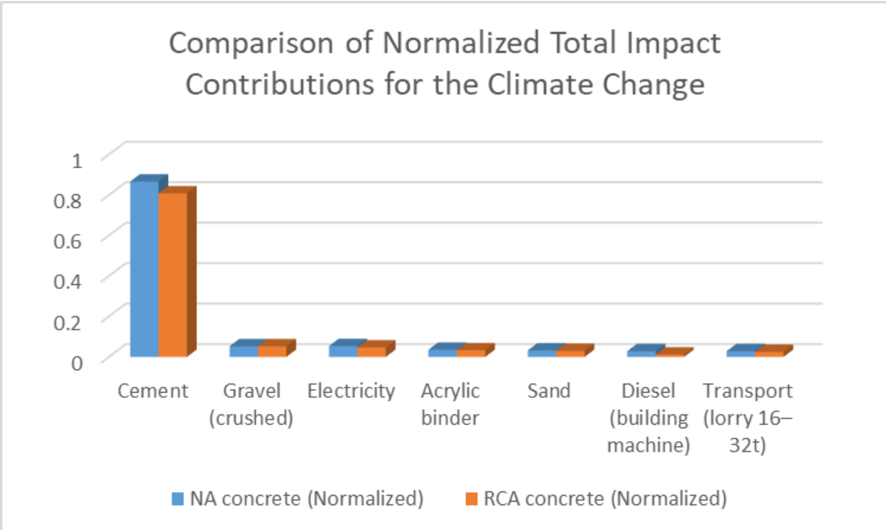

Figure 5.2: Comparison of normalized total impact contributions for the Climate Change category between NA and RCA concrete systems.

The results show that the production of cement is the dominant source of greenhouse gas emissions in both mixes. For NA concrete, cement accounts for approximately 0.87 of the total normalized contribution, while in RCA concrete this value decreases slightly to about 0.81.
This reduction is associated with the partial replacement of virgin aggregates by recycled concrete aggregate (RCA), which marginally reduces cement dependency but introduces additional contributions from aggregate preparation and transportation.

The aggregate related flows, including sand and crushed gravel, show a combined normalized contribution of roughly 0.08 in the RCA system compared to only 0.03 in the NA system.
This increase is mainly due to the extra processing energy and mechanical treatment required to produce recycled coarse aggregates. Although the relative share of aggregate impacts rises, their absolute contribution remains small compared to the cement component.

The electricity and acrylic binder flows contribute similarly in both systems (around 0.05 and 0.03, respectively), indicating that the introduction of recycled aggregates does not substantially affect the energy demand or chemical input stages.Together, these flows represent less than 10 % of the total GWP in either system.

A modest difference is observed in fuel and transportation activities. In the NA concrete system, the freight transport of materials (lorry 16–32 t EURO6) represents approxi-

mately 0.03 of the normalized total, whereas the operation of diesel-powered construction equipment in the RCA system contributes around 0.01.
This outcome suggests that material hauling plays a slightly larger role in NA concrete,while RCA concrete shifts a portion of emissions toward onsite fuel consumption.

Overall, Figure 5.2 demonstrates that, despite variations in secondary flows, cement production remains the primary environmental hotspot in both systems, responsible for more than four-fifths of the total normalized climate-change impact.The substitution of natural aggregates with recycled materials introduces additional but relatively minor effects from aggregate processing and transport.
Hence, future strategies to reduce the carbon footprint of concrete should prioritize lowering cement content through the use of supplementary cementitious materials, improved mix designs,or low carbon binders, while optimizing the logistics of recycled-aggregate handling to prevent offsetting environmental gains.

Normalized Energy Resource Impacts

Figure 5.3 compares the normalized total impact contributions of major input flows for the *Energy Resources* impact category obtained from the life cycle assessment of the NA and RCA concrete mixes.
Normalization was applied to express each flow as a dimensionless share of the total cumulative energy demand within its own system, facilitating comparison of relative importance rather than absolute magnitudes.

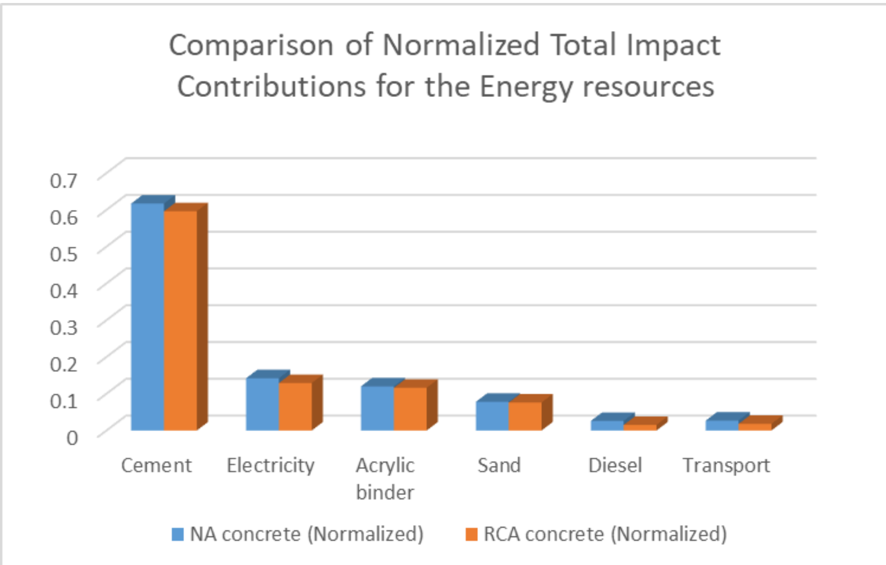

Figure 5.3: Comparison of normalized total impact contributions for the Energy Resources category between NA and RCA concrete systems.

The results clearly show that cement production has the largest share of energy use in both mixes.
It makes up roughly 60% of the total energy demand, which is expected since the production of cement requires a high amount of heat and fuel. Even though the RCA mix has a slightly lower total energy use, the normalized share of cement looks a bit higher because the other flows take up a smaller portion of the total.

Electricity and the acrylic binder come next, both with similar shares of around 12–14%. This means that replacing natural aggregate with recycled aggregate does not really change the amount of energy needed for these materials.The sand flow has a moderate contribution (around 7–8%), while diesel and transport have the smallest shares, both under 5%. These are mainly related to equipment use and material handling.

In general, Figure 5.3 shows that the RCA concrete uses less total energy overall, but the distribution pattern between the different inputs remains very similar to the NA mix. Cement production is still the main hotspot in both systems, so any reduction in cement content or improvement in its manufacturing efficiency would have the biggest impact on lowering the overall energy consumption of the concrete.

Normalized Ozone Depletion Impacts

Figure 5.4 presents the normalized total impact contributions for the Ozone Depletion category for both NA and RCA concrete mixes. The normalization was used to identify how much each process contributes within its own system and to highlight the most influential stages in this impact category.

The results clearly show that cement production is the major contributor in both systems. It accounts for more than half of the total impact, which is expected since cement manufacturing involves energy-intensive processes and emissions associated with high-temperature kilns. Although the total ozone depletion potential of the RCA concrete is slightly lower than that of the NA concrete, the relative share of cement in the RCA mix appears slightly higher because the overall impact in this system is smaller.

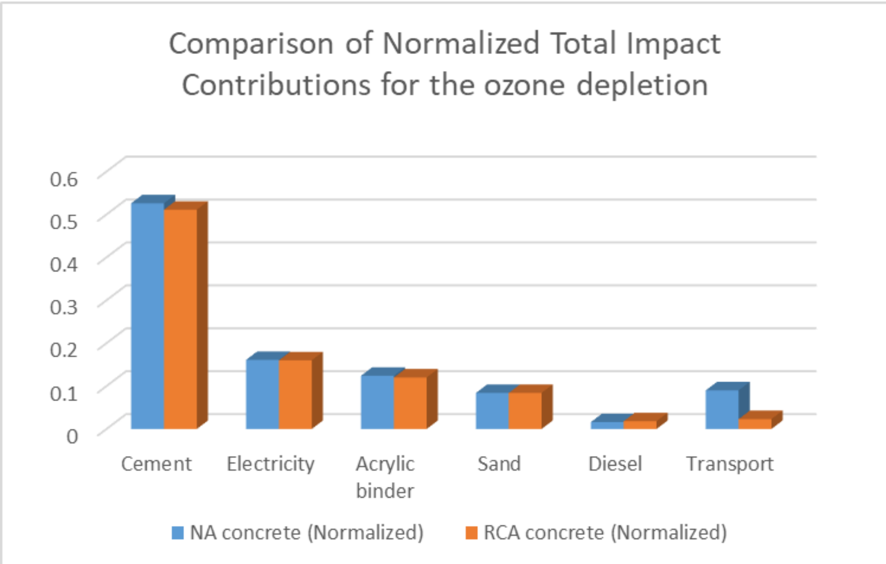

Figure 5.4: Comparison of normalized total impact contributions for the Ozone Depletion category between NA and RCA concrete systems.

Electricity comes next after cement, with a share of about 16–18%. This small increase in the RCA system can be linked to the extra electrical energy needed for the recycling and crushing of aggregates. The acrylic binder contributes around 12–13% in both systems, indicating that this component is not strongly affected by the change in aggregate type.

The contributions of sand, diesel, and transport are relatively low, all below 10% of the total impact.
However, the pattern between them slightly changes: in the RCA system, the share of transport decreases due to reduced hauling of natural aggregates, while diesel increases because of the additional fuel used during the processing of recycled materials.

In summry, Figure 5.4 shows that both systems follow a very similar trend in the ozone depletion category. The replacement of natural aggregate with recycled aggregate helps to reduce the total ozone depletion potential slightly,but cement production still remains the main part for this environmental impact.
This means that future reductions in this category should mainly focus on optimizing cement usage and improving its production efficiency, rather than changes in the aggregate type alone.

Water Use Impacts

Finally, in the last part of the analysis, it can be concluded that the difference in water use between NA and RCA concrete is minimal.Figure 5.5 illustrates the normalized contributions of the main processes to the Water Use category for both NA and RCA concrete. The normalization approach helps to highlight how each process contributes within its own system, making the comparison more balanced and meaningful.

In both mixes, cement production clearly dominates water consumption, contributing around 55–56% of the total. This dominance is linked to the water-intensive steps in cement manufacture, such as raw material blending, cooling, and dust management. Although RCA concrete records a slightly higher total water use, the difference between the two mixes is quite small, showing that replacing natural aggregates with recycled ones does not significantly alter the overall pattern of water demand.

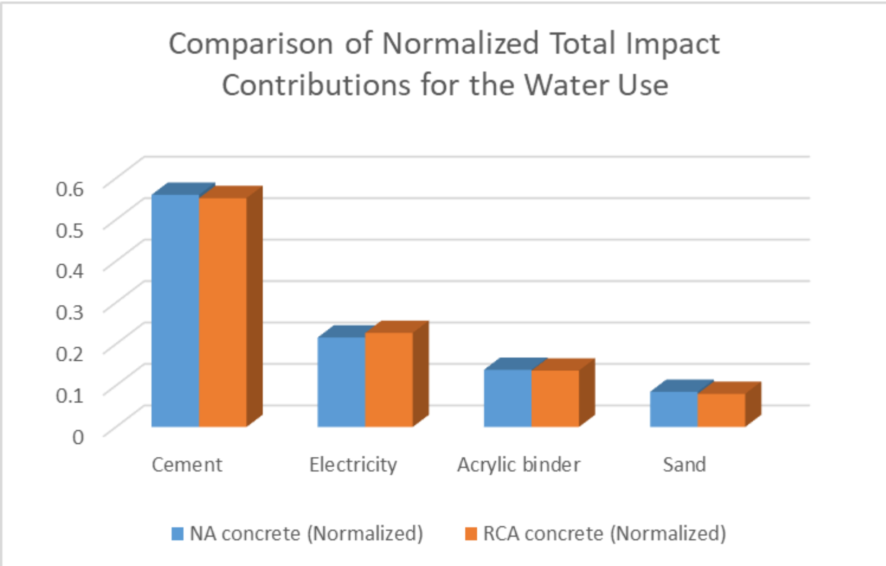

Figure 5.5: Comparison of normalized total impact contributions for the Water Use category between NA and RCA concrete systems.

The share of electricity use is the next most significant, and it appears a bit higher in the RCA system.

This can be attributed to the additional electrical energy required for processing recycled aggregates, such as crushing and screening, which indirectly increases water-related impacts. The acrylic binder and sand show relatively minor effects, together making up less than 25% of the total.

Their close values between the two mixes indicate that these processes are not strongly affected by the type of aggregate used.

5.3 Hotspot Analysis with Sankey Diagrams

To get a better understanding of how different processes contribute to the overall impacts, Sankey diagrams were created for the Climate Change, Energy Use, and Water Use categories in all three systems: NA concrete, RCA concrete, and the mix produced in the laboratory. These diagrams help to show where the main environmental burdens come from by displaying the flow of impacts through each life cycle stage. The width of each line represents how much that process contributes to the total impact, making it easier to see which materials or steps are more dominant.

The data used in the Sankey diagrams come from the pre-normalized results of the LCA.
All values were calculated based on the production of 1 m^3 of concrete, which is the functional unit of this study. This means that the diagrams show the total amount of impact linked to each process before any normalization or scaling.
By presenting the data in this way, the Sankey diagrams work alongside the previous tables and figures to show how impacts build up across the entire production chain—from raw material extraction and electricity use to the final concrete product.
This visual form makes it easier to identify the main sources of environmental load and compare how the contribution of each process changes among the three types of concrete.

5.3.1 Climate Change Category

To understand where greenhouse gas emissions originate within the production systems, Sankey diagrams were prepared for the natural aggregate (NA) and recycled coarse aggregate mixes.
Each diagram illustrates the flow of emissions for 1 m³ of concrete, and the width of every branch represents its relative contribution to the total climate-change impact.

For NA concrete (Figure 5.6), the diagram shows a clear dominance of cement production, which is responsible for roughly 80 % of the total CO_2 equivalent emissions.
This large share results from fuel combustion and the release of CO_2 during clinker formation.
Other noticeable contributors include electricity generation, gravel extraction , and sand production .Smaller but visible flows come from the acrylic binder, transport, and diesel use, while tap-water consumption contributes almost nothing to the overall total.

The RCA concrete system (Figure 5.7) displays a very similar structure.
Cement again dominates, with a slightly higher share—close to 85% reflecting that the use of recycled aggregates does not alter the role of cement in driving emissions.
The proportions of electricity and binder are comparable to the NA mix, but the flows related to gravel extraction and transport shrink because less natural material is mined and hauled.
A new, relatively small stream appears for inert-waste treatment (0.4%), representing the management of recycled aggregates after processing.

When both systems are compared, the diagrams show that the introduction of recycled aggregates reduces some upstream impacts, especially those tied to natural aggregate production and transportation.
However, the effect on the overall carbon footprint remains minor, since cement alone accounts for more than four-fifths of the total emissions. The Sankey diagrams make this imbalance clear: the width of the cement branch overwhelms all others.

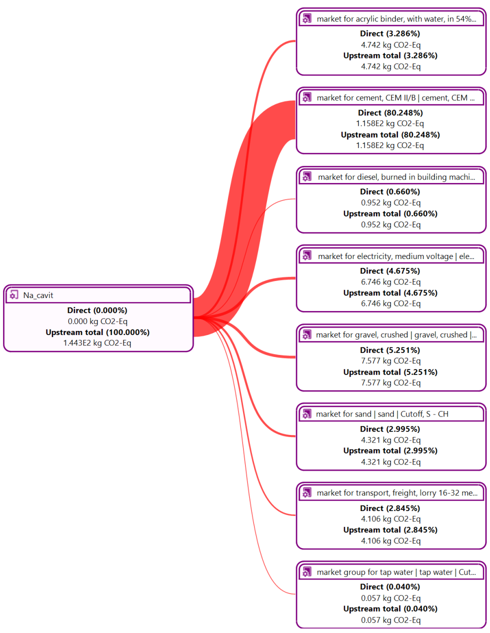

Figure 5.6: Sankey diagram showing the contribution of different processes to the Climate Change category for NA concrete.

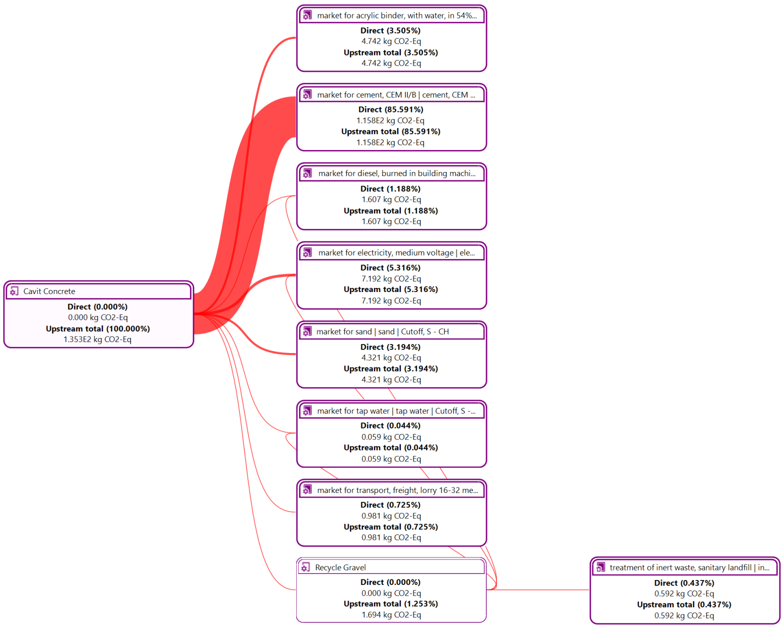

Figure 5.7: Sankey diagram showing the contribution of different processes to the Climate Change category for RCA concrete.

In summary, both systems share a similar emission pattern, with only small differences caused by aggregate substitution.
Using RCA can lower extraction- and transport-related impacts, but the cement stage remains the dominant hotspot controlling the climate change potential.
Meaningful reductions will therefore depend on actions such as lowering cement content, improving kiln efficiency, or using alternative binders rather than changes in aggregate type.

5.3.2 Energy Resources Category

To evaluate how energy consumption is distributed throughout the production systems, Sankey diagrams were developed for both the NA concrete and RCA concrete mixes under the Energy Resources category. Each diagram illustrates the total energy demand for the production of 1 m³ of concrete, with the thickness of the flows indicating the relative share of each process in the overall energy use.
These diagrams help identify the life cycle stages that consume the most energy and therefore have the highest potential for improvement.

For the NA concrete system (Figure 5.8), energy use is dominated by cement production, which accounts for about 53% of the total net calorific value.
This strong contribution reflects the large amount of thermal energy required during clinker formation.
The next highest contributors are electricity generation (11%), gravel production (11%), and acrylic binder manufacturing (10%). Each of these stages involves processes such as mechanical crushing, grinding, and chemical synthesis, all of which are energy-intensive. Smaller portions of the total energy use come from sand extraction (7%), transport (6%), and diesel combustion (1%), while water use represents less than one percent, showing that its impact on energy demand is minimal.

The RCA concrete system (Figure 5.9) shows a similar distribution, though the overall total energy demand is slightly lower than in the NA case.
Once again, cement remains the main hotspot, contributing around 61% of the total energy use.
However, the energy associated with transport and gravel extraction decreases considerably because part of the natural aggregate is replaced by recycled material.
This substitution not only avoids the extraction of virgin resources but also reduces the hauling distance for aggregates. A new flow appears for inert-waste treatment (1.6%), which accounts for the energy used in the recycling process and the handling of construction waste.
Meanwhile, the share of electricity (14%) and acrylic binder (12%) is slightly higher compared to NA concrete, showing that these processes still play an important role in total energy consumption.

When comparing both systems, it becomes clear that cement production is again the key driver of energy use, dominating the diagrams in both cases. Although the RCA system introduces additional steps such as waste treatment, the overall energy demand remains comparable because the energy savings from reduced aggregate extraction and transport nearly offset these extra processes.
The Sankey diagrams demonstrate that material substitution alone has limited influence on the total energy balance of concrete, as most of the energy demand stems from cement manufacturing and related high temperature operations.

In conclusion, both diagrams indicate that the cement stage is the main hotspot for energy consumption, followed by electricity and binder production.
The adoption of recycled aggregates provides moderate improvements by reducing upstream energy use in mining and transport. However, any major reduction in energy consumption will depend largely on innovations within the cement sector itself—such as fuel substitution, kiln efficiency improvements, or alternative low energy binders.

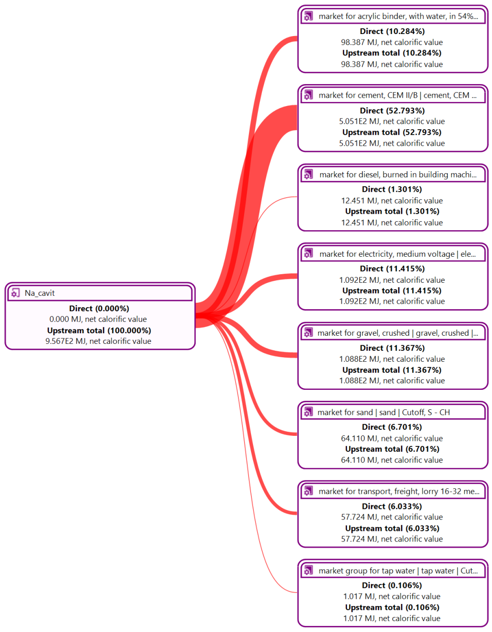

Figure 5.8: Sankey diagram showing the contribution of different processes to the Energy Resources category for NA concrete.

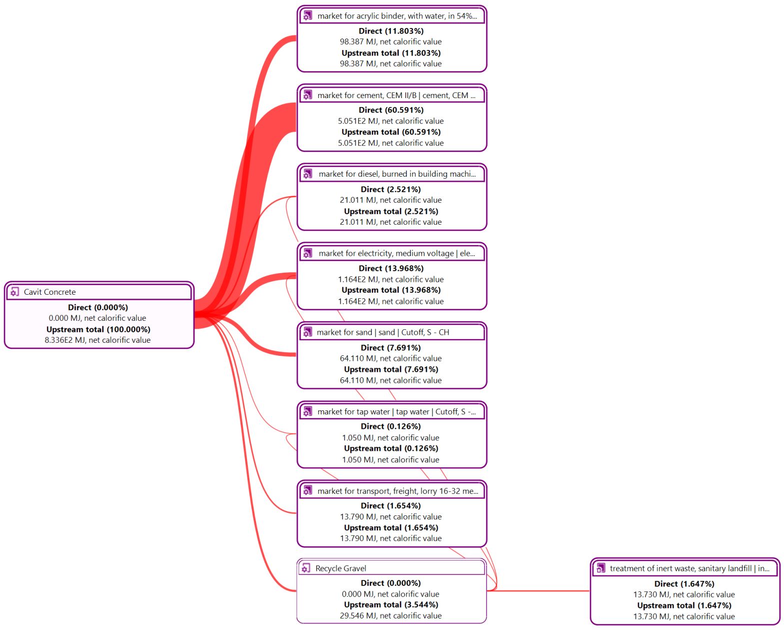

Figure 5.9: Sankey diagram showing the contribution of different processes to the Energy Resources category for RCA concrete.

5.3.3 Ozone Depletion

Figures 5.10 and 5.11 show how different stages in the life cycle of NA and RCA concrete contribute to ozone depletion. The results are given in kg CFC-11 equivalent for producing one cubic meter of concrete. These diagrams make it easier to see how each input adds up to the total and how the use of recycled materials changes the pattern of contributions.

For the NA concrete, the largest part of the ozone-depleting emissions comes from cement production, which makes up around 46% of the total. This is expected since cement manufacturing involves high energy use and combustion processes that indirectly release ozone-depleting gases during fuel extraction and electricity generation. The second biggest share belongs to electricity production, about 14%, showing how power generation still plays a noticeable role in the total. The acrylic binder adds another 11%, while gravel and sand extraction together account for roughly 18%. These processes depend on machinery and transport, both of which use energy and release small amounts of emissions. Transport itself contributes about 8%, while diesel has the lowest share at roughly 1%. Altogether, the NA diagram shows that the emissions are spread across several steps, although cement production is clearly the most important one.

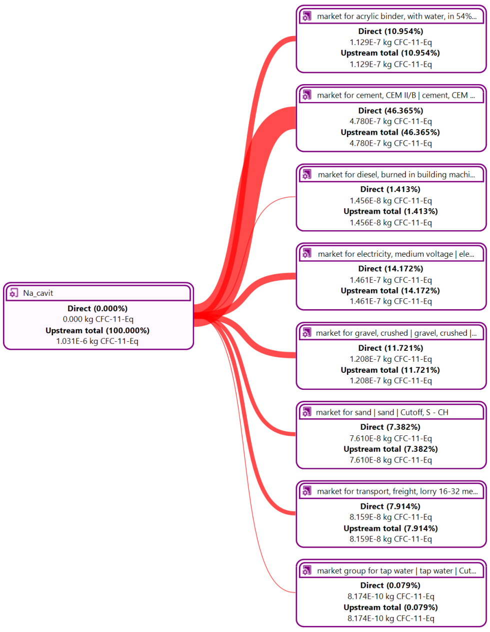

Figure 5.10: Sankey diagram for ozone depletion impact of NA concrete.

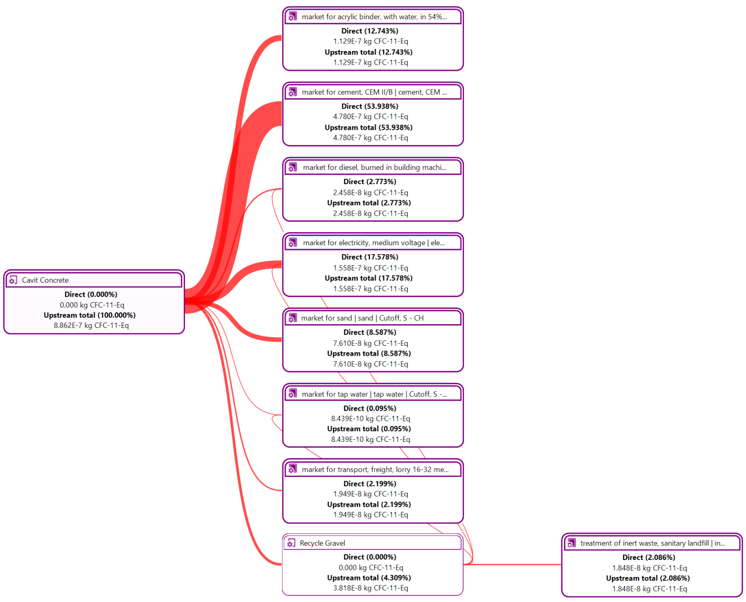

Figure 5.11: Sankey diagram for ozone depletion impact of RCA concrete .

In the RCA concrete, the general trend is quite similar, but a few shifts can be noticed. Cement production still dominates, this time contributing a bit more, around 54%, followed by electricity, which increases slightly to about 17%. The acrylic binder is close behind at 12–13%. The shares for sand and transport become smaller since part of the natural material is replaced with recycled aggregates. One new flow appears, representing inert waste treatment, which adds roughly 2%. This part comes from handling and processing the recycled material, something that doesn't exist in the NA system. Even though this introduces an additional stage, it also replaces part of the raw aggregate extraction and transport energy.

When the two systems are compared, it's clear that using recycled aggregates doesn't drastically change the total ozone depletion results. The overall emissions stay quite similar, but the sources shift slightly. The RCA mix reduces some upstream impacts from quarrying and transport but adds new emissions from waste processing. Both systems are mainly affected by cement and electricity, which together cause over 70% of the total impact. This means that, in terms of ozone depletion, improving the efficiency of cement production and using cleaner electricity would be much more effective than changing the type of aggregates used.

5.3.4 Water Use

The Sankey diagrams in Figures 5.12 and 5.13 illustrate how water is consumed across different stages in the life cycle of NA and RCA concrete. Each line represents a process, and the flow thickness shows its share in the total water use, expressed in m^3 world equivalent deprived for producing one cubic meter of concrete. Unlike the previous impact categories, water use is mostly connected to raw material handling and less to direct fuel or energy use.

In the NA concrete, the largest part of the water footprint comes from gravel extraction, which takes up almost half of the total water demand, around 49%. Quarrying activities are usually water-intensive since water is needed to wash the material and control dust. The next major contributor is cement production, at roughly 28%, which reflects the water used during the raw meal preparation, cooling, and other production steps. Electricity generation also plays a role, accounting for about 11%, mostly due to the cooling water used in power plants. Other materials such as sand and acrylic binder make smaller contributions, around 4% and 7%, respectively. Transport and diesel use barely register, each below 1%. Overall, the NA Sankey diagram (Figure 5.12) clearly shows that the majority of water use originates upstream, mainly in the extraction and material production stages, not during mixing or construction.

For the RCA concrete, the pattern changes quite a bit. Because recycled aggregates replace part of the natural gravel, the total water use is cut almost in half, down to about 18.9 m^3 world eq deprived. Here, cement production becomes the main hotspot, taking up around 55% of the total. This is followed by electricity, which rises to about 22%, and the binder, around 13%. The contribution from sand stays close to 8%. A small new share, roughly 0.4%, appears from inert waste treatment, related to processing and cleaning the recycled aggregates. Even though it adds a new flow, it's still small compared to the water saved from reduced quarry operations.

What stands out when comparing the two systems is the clear trade-off: RCA concrete slightly increases water use in some upstream processes, but overall the system performs better. The removal of high-water-demand gravel is the biggest advantage. The Sankey diagrams make this easy to visualize in the RCA mix, the thick gravel flow in the NA diagram almost disappears, while the cement and electricity lines become relatively more dominant. This shift underlines how material substitution can significantly

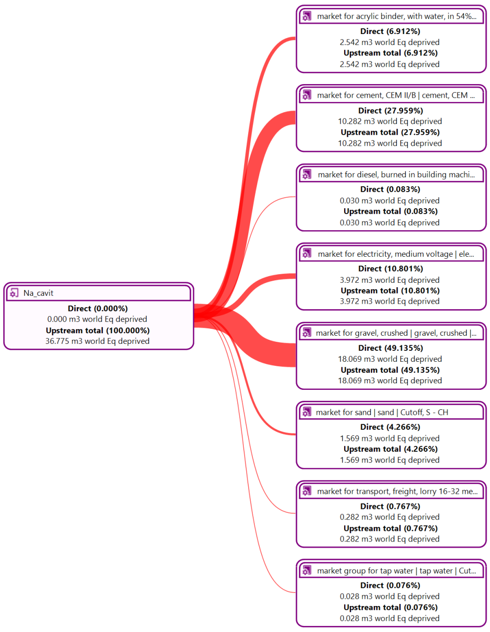

Figure 5.12: Sankey diagram for water use impact of NA concrete.

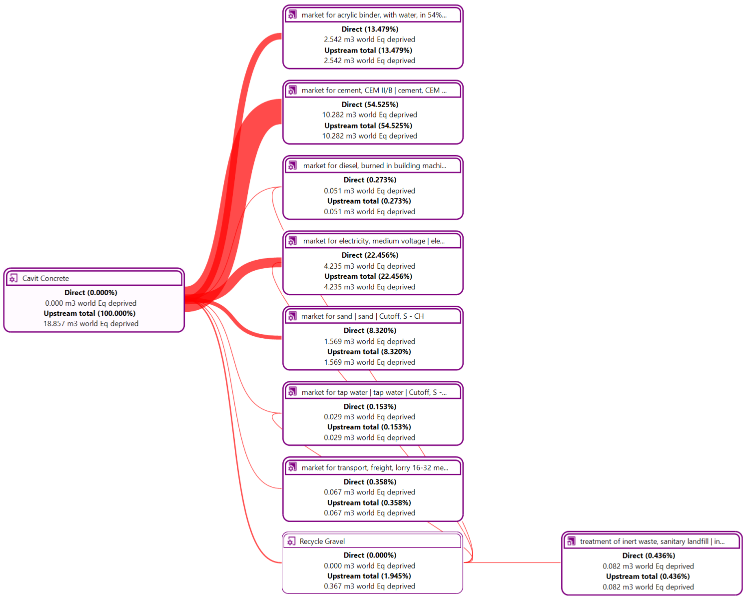

Figure 5.13: Sankey diagram for water use impact of RCA concrete.

reduce total water consumption, even if it slightly changes the internal distribution of impacts.

5.3.5 Laboratory Scale LCA of RCA Concrete

To check how the real mix behaves compared to the modeled results, a small LCA was also done for the concrete made in the lab using recycled aggregates. The goal here was not to get precise or industry level data but to see if the same general trends appear when the process is done at a smaller scale. The values come from what was actually used in the lab materials, water, electricity, and transport distances and then entered into the same LCA method as the main study.

Figures 5.14 to 5.17 show the Sankey diagrams for the lab-scale RCA mix. The main categories studied are climate change, energy resources, ozone depletion, and water use. All results are based on one cubic meter of concrete produced in the lab.

In the climate change category, shown in Figure 5.14, the highest impact comes from electricity, which makes up more than half of the total emissions (around 54%). This makes sense since all mixing, curing, and equipment use were powered directly from electricity in a small space with no energy recovery. The transport of materials is the second largest source at about 38%, because materials were moved in small amounts using a passenger car, which is less efficient than large-scale transport. Cement contributes about 7%, while the other processes have only small shares.

The energy use results (Figure 5.15) show almost the same pattern. Electricity is again dominant, followed by transport and cement. The total energy demand is around 5.77 MJ, lower than the modeled RCA system, but still higher per unit of material because lab work is not optimized for energy use.

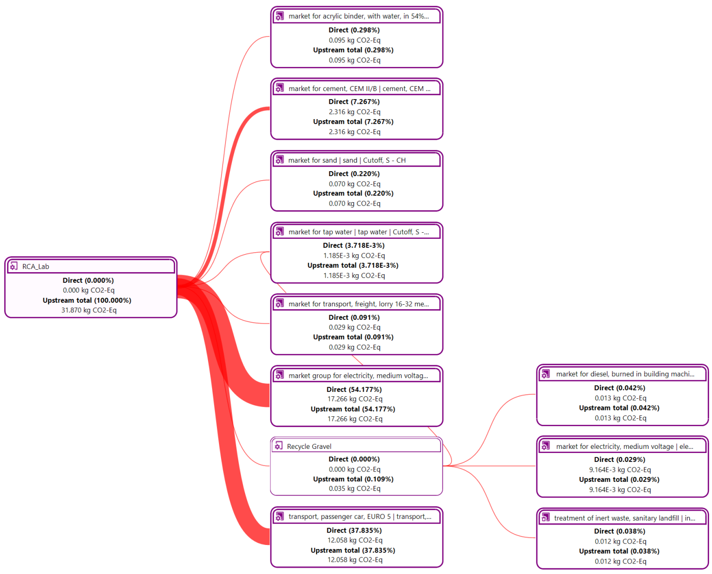

Figure 5.14: Sankey diagram for climate change impact of laboratory RCA concrete.

In ozone depletion (Figure 5.16), electricity and transport again have the largest shares, making up nearly all of the total. The water use diagram (Figure 5.17) shows that electricity accounts for about 87% of the total, followed by transport (10%) and cement (around 2%). The total water footprint is roughly 12 m³, lower than the modeled system because no large-scale washing or pumping was required.

Overall, the lab scale LCA shows the same general trends as the full RCA system, with

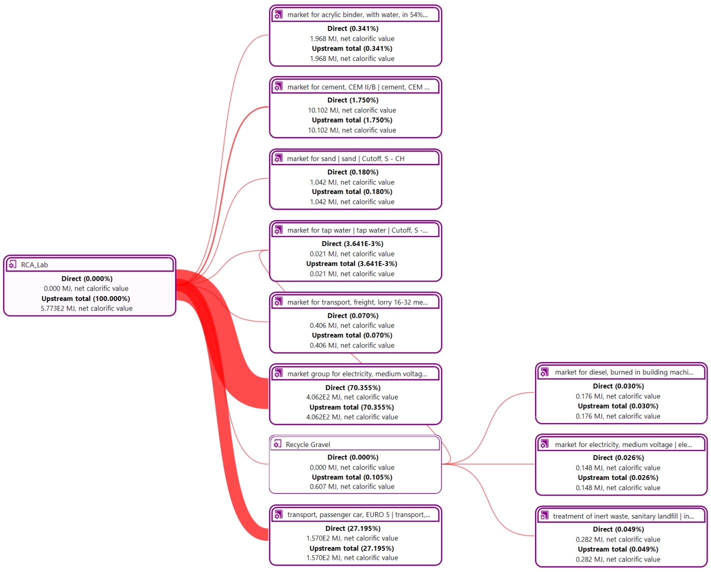

Figure 5.15: Sankey diagram for energy resource use of laboratory RCA concrete.

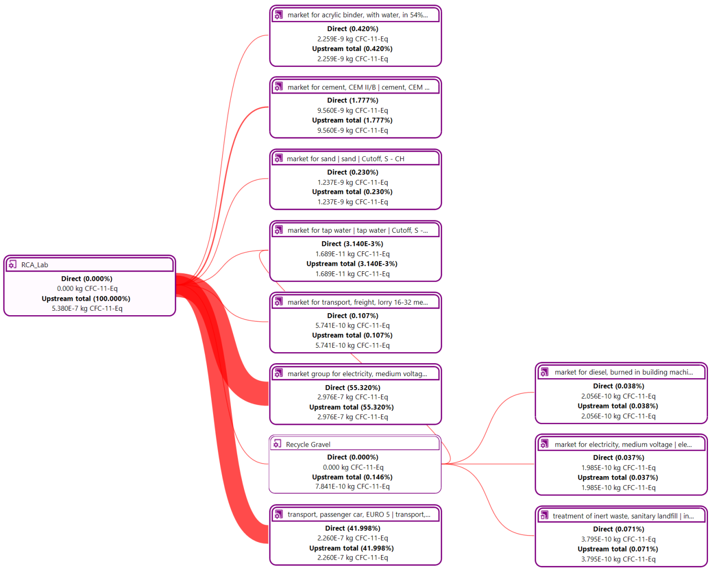

Figure 5.16: Sankey diagram for ozone depletion impact of laboratory RCA concrete.

electricity and transport as the biggest contributors. The total values are smaller, but the structure of the impacts stays consistent. This supports that even at small scale, the main environmental hotspots come from energy use and cement production.

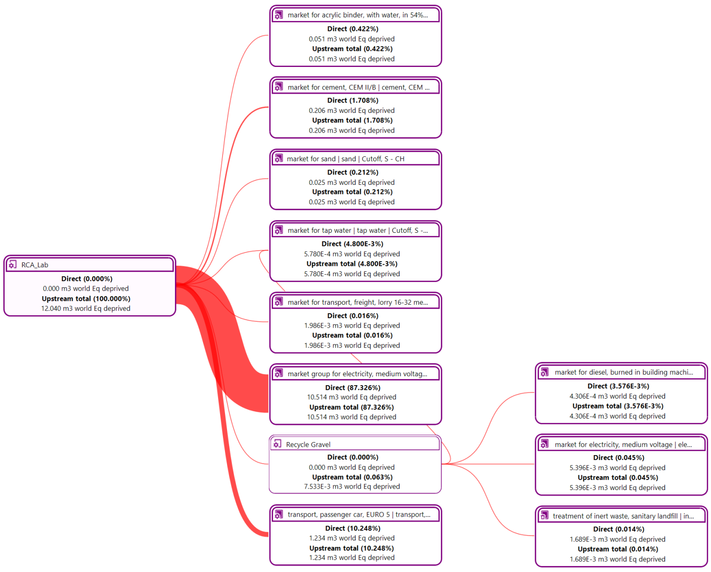

Figure 5.17: Sankey diagram for water use impact of laboratory RCA concrete.

5.4 Summary of Results

The results show that using recycled aggregates gives a small but clear improvement compared to natural aggregate concrete. The differences are not big, but they go in the same direction for most categories.

The largest change is in water use. The RCA mix needs much less water because there is no washing or cleaning step like in quarry operations. This makes a big difference in the total water footprint.

For climate change, the RCA mix produces about 6–7% less CO_2 . This is mostly because it avoids quarry extraction and long-distance transport. Cement production is still the main source of emissions in both mixes.

Energy use also drops slightly with RCA. Recycling uses some electricity, but overall it needs less fuel than quarrying and moving natural aggregates.

The only category that increases a little is ozone depletion, and that comes from the extra electricity used in recycling. The increase is very small and doesn't change the overall result.

After normalization, climate change and energy use stand out as the main impacts. The others are much smaller in comparison.

In short, using recycled aggregates doesn't transform the footprint of concrete, but it helps in every key area. It cuts down water use, reduces energy and emissions a bit, and avoids the need for new raw materials. For normal construction and pavement work, RCA concrete can be a solid and more sustainable choice.

6 Discussion

6.1 Material and Design Efficiency

From the lab results, it was clear that the mix made fully with recycled coarse aggregates performed better than expected. The cubes reached an average compressive strength of about 11 MPa, which is only about 20–25% lower than the natural aggregate concrete produced by the company (around 15 MPa).
Considering that this mix was made completely from recycled materials, this is a good outcome.
It shows that, with the right proportions and use of additives, it is possible to make a workable and reliable concrete using only RCA.

The main reason for this result was the balanced blend between the 0–8 mm and 0–40 mm fractions and the use of the acrylic superplasticiser, which helped manage the higher water absorption.
This mix achieved good cohesion and workability during preparation, and even after curing, the samples behaved consistently during testing.
Reaching almost the same mechanical behaviour as natural aggregate concrete shows that RCA can be used efficiently without compromising the quality needed for road and pavement works.

6.2 Operational Improvements

During both the LCA and laboratory stages, some clear areas for improvement appeared. The first is cement use. Even though the aggregates were changed, the cement stayed as the main source of environmental impact, especially in the climate change and energy use categories. Reducing the cement content or replacing part of it with other materials like fly ash or slag could make a big difference in emissions.

Another area is the aggregate processing itself.Better washing and grading of RCA can lower water and energy demand.
If local recycling facilities are used, the transport distances become shorter, which helps reduce fuel-related emissions.
Finally, having more control over the moisture content of the RCA could make mix adjustments easier and reduce unnecessary cement additions during batching.

6.3 Net-Negative Emissions Potential

Right now, the concrete system is not carbon negative, but the results suggest that it could move in that direction in the future. If low carbon cement or partial cement replacement is combined with renewable electricity in the recycling process, the total footprint would drop sharply.
Also, natural carbonation during the life of the concrete can capture part of the CO_2 originally emitted.
Using fully recycled aggregates already avoids the impacts of quarrying and disposal,

which helps close the material loop. So, while the current version still has emissions, RCA-based concrete could become close to net-neutral if combined with greener energy and cement alternatives.

6.4 Interpretation (ISO 14044)

Following the ISO 14044 interpretation step, the results were checked for completeness and consistency.The goal was to compare two realistic concrete systems under the same conditions.
Both the life cycle and the experimental results were consistent: the RCA mix always showed slightly lower environmental impacts and only a small drop in strength.

This means the system model worked as intended, and the laboratory data helped confirm that the assumptions used in the LCA were realistic. In short, the interpretation confirms that RCA concrete can reduce the environmental load while still performing well enough for practical use. The small performance difference is acceptable, and with a few optimizations, the recycled mix can become a reliable alternative to natural aggregate concrete.

7 Conclusions and Recommendations

7.1 Summary of Contributions

This research combined practical laboratory work with life-cycle assessment to understand how using recycled concrete aggregates (RCA) affects both the performance and environmental footprint of concrete.
The first contribution was the detailed characterisation of RCA, including grading, water absorption, and shape tests, compared directly with company data.
This confirmed that the material used in the lab was representative of real-world production and suitable for mix design.

The second contribution was the development of a workable concrete mix made entirely from recycled coarse aggregates.
Through several trials, a balanced combination of 0–8 mm and 0–40 mm fractions was achieved, producing concrete with an average compressive strength of around 11 MPa.
This result shows that full RCA substitution can still deliver reliable material for road bases and secondary applications.

The third contribution was the integration of experimental work with a full environmental analysis.The LCA compared natural aggregate (NA) and RCA concretes using the EF 3.1 method and showed consistent reductions in climate change, energy use, and water consumption when RCA was used.Even though the strength was slightly lower, the environmental improvements were clear and measurable.Bringing these two parts together, technical testing and environmental modeling, gives a complete view of what recycled concrete can offer in practice.

7.2 Limitations of the Study

There are several limitations that should be noted. The most obvious one is that the experimental concrete was produced on a small laboratory scale, not under industrial batching conditions. The curing and mixing equipment were limited, which may have affected the final strength and surface finish of the specimens.
The molds used were lightweight and not designed for long water curing, so the results should be interpreted as preliminary rather than definitive.

In the LCA part, the assessment relied on data from Ecoinvent and literature averages rather than direct measurements from production.
While this approach ensures comparability, it may not fully capture regional variations in transport distances, electricity sources, or plant efficiency. The analysis was also limited to four impact categories, climate change, energy use, water use, and ozone depletion, meaning that other important effects like land use, resource depletion, or toxicity were not covered.

Finally, only one mix design and one recycled aggregate source were studied. Different aggregate qualities or partial replacement ratios might produce other outcomes.

7.3 Recommendations for Future Research

Future research should build on these findings by moving from small-scale testing to full scale concrete production.
Testing the same RCA mix in real batching conditions would help verify the strength, durability, and consistency under industrial control. It would also make it possible to evaluate the long-term behaviour of RCA concrete under real weather and loading conditions.

Further work could also look at ways to reduce the cement content, for example by using materials like fly ash, slag, or calcined clays. These can help cut emissions and costs without compromising durability. Another possible direction is CO_2 curing or carbonation, which would allow the concrete to take back some of the CO_2 released during cement production. A next step could also be to see whether it is possible to produce concrete with a higher mechanical strength when using recycled aggregates or recycled sand. It would be worth testing if replacing part of the natural aggregate with recycled material could actually improve the strength, or at least keep it at a similar level.

Finally, future LCAs should include a wider range of categories and sensitivity analyses.This would make it easier to understand trade-offs between impact areas, especially when recycled aggregates are combined with alternative binders or new transport systems.Collecting site specific data from recycling plants and ready-mix producers would also improve accuracy and strengthen the link between environmental modeling and real construction practice.

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