Concrete Waste Recovery and Emissions Reductions in the Norwegian Concrete Industry

Environmental Aspects of a Concrete Producer in Southern Norway

Yvonne-Marie Miniggio

Supervisors

Reyn Joseph O'Born, UiA

Øystein Mortensvik, Ribe Betong AS

University of Agder Norway, 2022

Faculty of Engineering and Science
Department of Engineering Sciences

Group Statement

Den enkelte student er selv ansvarlig for å sette seg inn i hva som er lovlige hjelpemidler, retningslinjer for bruk av disse og regler om kildebruk. Erklæringen skal bevisstgjøre studentene på deres ansvar og hvilke konsekvenser fusk kan medføre. Manglende erklæring fritar ikke studentene fra sitt ansvar.

1.	Jeg erklærer herved at min besvarelse er mitt eget arbeid, og at jeg ikke har brukt andre kilder eller har mottatt annen hjelp enn det som er nevnt i besvarelsen.	☒
2.	Jeg erklærer videre at denne besvarelsen: - ikke har vært brukt til annen eksamen ved annen avdeling/universitet/høgskole innenlands eller utenlands. - ikke refererer til andres arbeid uten at det er oppgitt. - ikke refererer til eget tidligere arbeid uten at det er oppgitt. - har alle referansene oppgitt i litteraturlisten. - ikke er en kopi, duplikat eller avskrift av andres arbeid eller besvarelse.	☒
3.	Jeg er kjent med at brudd på ovennevnte er å betrakte som fusk og kan medføre annullering av eksamen og utestengelse fra universiteter og høgskoler i Norge, jf. Universitets- og høgskoleloven §§4-7 og 4-8 og Forskrift om eksamen §§ 31.	☒
4.	Jeg er kjent med at alle innleverte oppgaver kan bli plagiatkontrollert.	☒
5.	Jeg er kjent med at Universitetet i Agder vil behandle alle saker hvor det forligger mistanke om fusk etter høgskolens retningslinjer for behandling av saker om fusk.	☒
6.	Jeg har satt meg inn i regler og retningslinjer i bruk av kilder og referanser på biblioteket sine nettsider.	☒

Publishing Agreement

Fullmakt til elektronisk publisering av oppgaven

Forfatter(ne) har opphavsrett til oppgaven. Det betyr blant annet enerett til å gjøre verket tilgjengelig for allmennheten (Åndsverkloven. §2).

Alle oppgaver som fyller kriteriene vil bli registrert og publisert i Brage Aura og på UiA sine nettsider med forfatter(ne)s godkjennelse.

Oppgaver som er unntatt offentlighet eller tausehetsbelagt/konfidensiell vil ikke bli publisert.

Jeg gir herved Universitetet i Agder en vederlagsfri rett til å gjøre oppgaven tilgjengelig for elektronisk publisering:	☒ JA	☐ NEI
Er oppgaven båndlagt (konfidensiell)? (Båndleggingsavtale må fylles ut) - Hvis ja:	☐ JA	☒ NEI
Kan oppgaven publiseres når båndleggingsperioden er over?	☐ JA	☐ NEI
Er oppgaven unntatt offentlighet? (inneholder taushetsbelagt informasjon. Jfr. Offl. §13/Fvl. §13)	☐ JA	☒ NEI

Acknowledgements

This master's thesis has been prepared at the Department of Engineering Science as part of the Civil and Structural Engineering master's program at the University of Agder. The master's thesis is the final assignment in the course BYG508 and was prepared in the fourth and final semester.

Firstly, I would like to thank Ribe Betong for providing me with the opportunity to write for them. I have been fortunate to be surrounded by talented and knowledgeable people who have contributed to my work with this thesis. I want to thank my supervisors, Reyn Joseph O'Born (UiA) and Øystein Mortensvik (Ribe Betong), for always believing in me and creating an encouraging environment giving me the courage and strength to overcome difficulties and setbacks.

Further, I would like to express my sincere gratitude to the employees at Ribe Betong: Harald Johannessen, Ingrid Stenbråten, Katarzyna Kamila Przyworska, Lene Moen, Stein-Harald Isaksen, Jaran Finden, Hans Kristian Birkenes and Amit Verma, for their help, patience and understanding. To Solomon Adomako at UiA for sharing his knowledge and showing me the procedures for the Los Angeles test. To Kristine Fagerheim and Sven-Henrik Norman at Mapei for sharing their passion for increasing the sustainability of concrete and aiding in the data collection. To Rita Sølvi Ditlefsen at the university laboratory for always making me feel at home. And to Geir Norden at Leca Norge and all the other great people I have encountered during my work on this master's thesis.

Finally, I would like to thank my family and friends for their love, comprehension and reassurance through the writing of this thesis and my engineering studies.

Yvonne-Marie Miniggio

3rd of June 2022, Grimstad

Abstract

Concrete is recognised as one of the most available and durable building materials. As a result, it is widely used and in large quantities. This is in its significant contribution to our greenhouse gas emissions and depletion of natural resources. This master's thesis explores the sustainability of concrete by examining concrete manufacturers and their potential to improve their sustainability profile. The research question has been *how can the concrete industry improve its sustainability profile with the re-use of surplus fresh concrete and its by-products?* The methods used to answer the question include life cycle assessment, empirical work, and a literature review. The concrete producer Ribe Betong was selected as a case example for the thesis.

The literature review and case study combined with the life cycle assessment showed that in addition to greenhouse gas emissions from concrete, concrete waste exposes our nature to undesirable climate impacts. The empirical work consisted of a full-scale dry washing test and laboratory work on the durability of the aggregate used for washing. Even though the aggregates can be seen as suitable for the production of new concrete, the washing procedure leads to a higher environmental footprint from the concrete manufacturer and produces large amounts of by-products.

It is found that concrete producers focus on sustainability but have improvement potential concerning their impact on the environment. A clear framework provides the prerequisites for achieving improvements and meeting expectations from society. Furthermore, proper understanding and competence can help create fertile ground for innovative and sustainable solutions for the concrete producers and their local environment.

Contents

List of Figures

List of Tables

1 | Introduction

The world will not evolve past its current state of crisis
by using the same thinking that created the situation.
∼ Albert Einstein ∼

This thesis aims to look at how to improve the sustainability profile of concrete manufacturers. This is important because large parts of the man-made climate impact lie with the construction industry. As is well known, concrete has a large climate footprint, and most of this is due to cement. This thesis will not look at what can be done to improve the climate footprint of cement but rather investigate other measures to improve the sustainability of the concrete producers. There is a growing focus on sustainability and the circular economy in our society, from the man in the street and youth movement to standards, policies, regulations and legislation.

The production of concrete is estimated to stand for 9% of greenhouse gas emissions, and 7 to 8% of this originates from the production of cement [1]. The concrete industry is responsible for 2.8 G tonnes of emitted CO_2 each year [1]. Compared to countries, the emissions from the concrete industry would be the world's third-largest country, after China and the United States with 10.18 and 5.29 G tonnes respectively [1]. Cement production is an energy-demanding process, and even though significant resources in the form of technical innovation and the use of green energy [1][2], and it stands for, and 2–3% of the global energy use [3]. The substantial amount of natural resources required to produce concrete is also an essential matter. To produce one tonne of clinker, an average of 1.22 tonnes of limestone and 0.31 tonnes of clay is needed [1]. The extraction and production of aggregate are both energy demanding and depletes our non-renewable resources [1].

Coffetti at al. [1] considers concrete to be more sustainable per kg of other building materials (for instance, wood, glass, steel and brick). Concrete is nevertheless used in large quantities, which leads to a high impact. The high quantity is also reflected in the amount of waste generated, as concrete is the main component in construction waste, as it represents approximately half of the building and demolition waste produced [4]. The amount of waste from building activities in Norway was 2.1 million tonnes in 2020 [5].

The re-use of concrete from construction and demolition waste has been a focus point for decision-makers and researchers for several years. However, the waste stream from the ready mix concrete plant is off today, a rather unresearched issue [6][7]. Of all ready mix concrete produced in Europe, approximately 2.5% is returned in a fresh state to the producer [6] and 1-4% of the concrete produced becomes concrete sludge waste [8]. Therefore, sustainable improvement of concrete and cementitious materials and progress for re-use of concrete demolition waste is not enough to ensure sustainable concrete production. The environmental impact of the concrete plant needs to be investigated, and solutions to improve its sustainability needs to be put in place.

2 Social Perspective

Climate change is impacting the livelihood of people all over the globe. Greenhouse gas emissions alter the global climate, and the magnitude of climate change will depend on the degree to which we achieve reductions in emissions. Rising seas, larger amounts and more frequent rainfall, extreme weather, landslides, floods, droughts and fires are increasing the risks related to climate change [9][10]. Indications from the World Economic Forum's (WEF's) Global Risk Report showed that the primary long-term risk of today's economy is the failure to mitigate climate change [1][11]. The natural catastrophes in 2021 resulted in a total of 2 500 billion NOK in global economic loss [12], in addition to the human casualties and the destruction of ecosystems [1]. In comparison, the Norwegian gross domestic product (GDP) was 3 568 billion NOK the same year [13]. By 2050, the sea level rising is estimated to be about 30 cm, and by the end of the century, the worst-case scenario estimates up to 2 m rising [1][14][15][16]. The sea level rising due to the melting of polar glaciers will not only affect the low land arias under 10 m above the current sea level, and the population of over one billion people living there [1][17], but it can also alter ocean currents, leading to weather and ecosystem disorders [1][18]. As temperatures are changing, the inhabitants of the arctic regions report the permafrost melting [19]. The thawing results in organic carbon being oxidised to CO_2. Estimates show that by 2100, 50-150 G tonnes of the stored carbon can be emitted [1][20]. A limitation to 1.5°C in the rise of temperature is crucial to avoid disastrous economic, social and environmental impacts [21]. The United Nations Environment Programme's (UNEP's) Emissions Gap Report of 2021 [22] states that by the end of the century, the global temperature will rise 2.7°C.

The challenges people face as a result of climate change confirm the need for change in how society is developing. The premises of nature must be reconciled with growth and development. Global economics and development have traditionally been based on extraction, manufacture and use, in which waste is discarded or incinerated. This is known as linear economy [23]. The circular economy can be seen as opposed to the linear economy. Resources, products and components are kept within the economic system and put to effective use for as long as possible [23]. This is accomplished by shearing, maintenance, re-use, re-manufacturing and recycling of available products and materials. At the same time, the level of raw material extraction is minimised, and the use of renewable resources is optimised [24].

The visualisation of circular economy seen in Figure 2.1 is known as the butterfly diagram [24]. The left section (green) presents the biological cycles, and the right (blue) the technical cycles. They are known as renewable flow management and stock management, respectively. The biological cycles include biodegradable products which can regenerate in nature. In the innermost cycles, those marked cascades, materials or products are used several times based on their applicability. For example, when biochemical materials are extracted for biogas production, the circularity is upheld by the remaining materials returning to nature for regeneration. Technical cycles usually consist of products and materials which are not renewable. The cycles that are closest to the axis in the centre are the ones that should first be employed. If the method can not be utilised, one moves to the next cycle. This is to ensure that the lifespan is as long and as useful as possible [24].

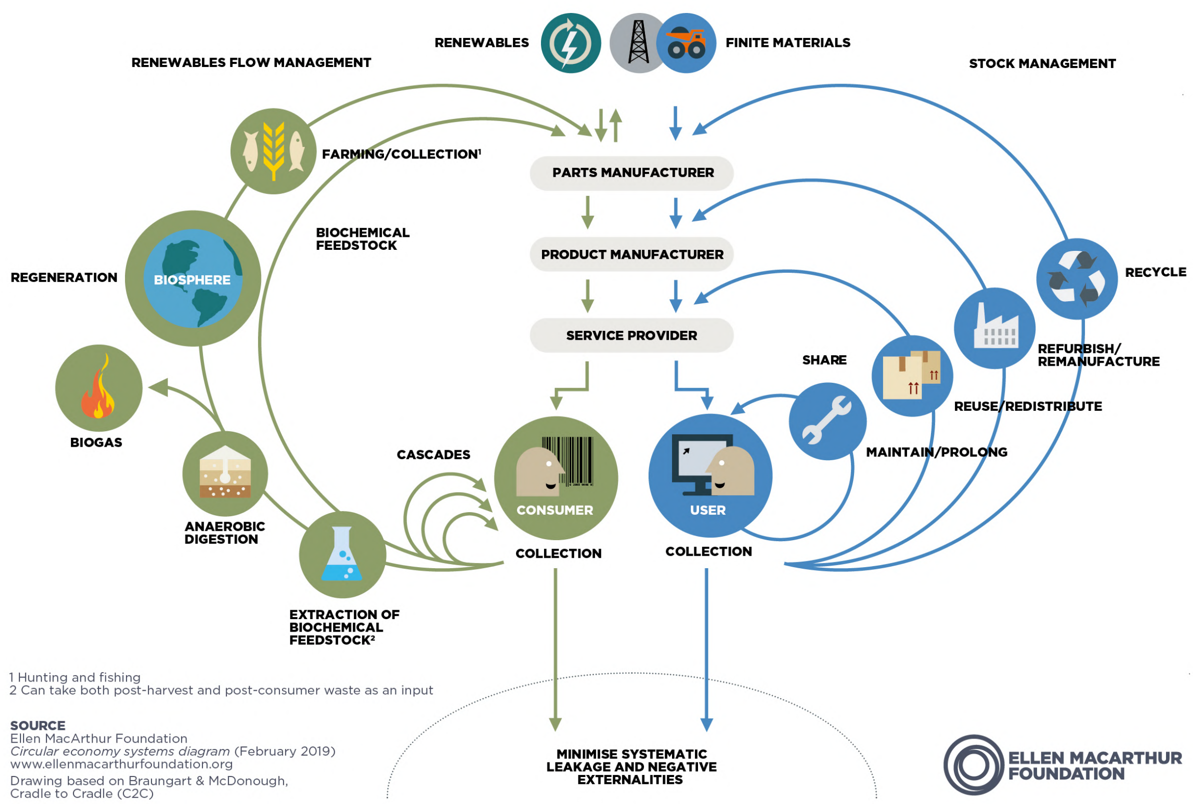


Figure 2.1: *The butterfly diagram of circular economy by the Ellen MacArthur Foundation [24]*

To ensure resource efficiency together with a modern and competitive economy, the European Union has approved in 2020 the action plan for circular economy known as the European Green Deal [25][26]. As a member of the European Economic Area (EEA) Agreement, Norway follows this set of policy initiatives for climate action. The objective is to protect the European natural environment and biodiversity and improve the welfare of people. It states that economic growth should be dissociated from these factors. In addition, it sets a request for zero net emissions of greenhouse gases by 2050 [25][26].

To achieve sustainable development, the United Nations (UN) has developed the Sustainability Goals (SDG) as a set of global guidelines to end poverty and inequality and ensure justice, and peace [27]. According to the Norwegian Environment Agency [23], a circular economy is vital in achieving the SDGs [23].

2.1 Corporate Social Responsibility

Goal 12 of the Sustainable Development Goals reads "*Ensure sustainable consumption and production patterns*" (Figure 2.2) [28]. Goal 12 can be related to corporate social responsibility. Ihlen [29] explains corporate social responsibility to be how businesses perceive their surrounding society. In terms of social standards, how they look after their employees, their owners and the environment. It is, in other words, how businesses' ethical, economic and legal considerations are taken into account in meeting society's expectations. The expectations of society can change over time, and companies need to adapt to their times [29].

Figure 2.2: *Goal 12* [28]

§ Target 12.2: *By 2030, achieve the sustainable management and efficient use of natural resources*

§ Target 12.5: *By 2030, substantially reduce waste generation through prevention, reduction, recycling and re-use*

The construction industry is one of the main contributors to global greenhouse gas emissions (GHG). In 2020 it stood for 38% of the total global energy-related CO_2 emissions [30]. The global goal of a net-zero carbon building stock by 2050 is estimated by the International Energy Agency (IEA) to be achievable if the direct building CO_2 emissions are decreased by 50% [30]. The CO_2 footprint from the global use of material increased from 2000 to 2017 with 70% [28]. The choice of materials and building customs lay the foundations for the lifetime of construction and its environmental impact. To ensure equal opportunities and future prospects for future generations, the world is in need of sustainable consumption and circular thinking in terms of waste management, strategies to eliminate pollution and ensuring the continuous regeneration of our natural environment and resources. [31]. At the same time, the world's population is growing at an annual rate of 1% [32][33]. Since 2007 it has grown with one billion, and with two billion since 1994 [33] and now has now in 2022 a total population of 7.95 billion people [32]. By 2050 the global population is estimated to reach 9.7 billion [33]. Today, the proportion of the population that lives in urban areas is larger than that of rural areas. In 2018, 55 % lived in urban areas, and by 2050, it is anticipated that 68% will be urbanised [34]. Therefore, urban expansion needs to be planned and managed to ensure sustainable consumption and production and the insurance of adequate infrastructure and public facilities [34]. This can be seen as the construction industry's social responsibility, two seemingly inconsistent human needs: ensuring infrastructure and housing for the growing population and protecting our environment [1].

2.2 Water and Sustainability

Water is the world's most widely used material, and the natural distribution of freshwater varies across the globe. When water becomes scarce, or water sources get polluted, it has a negative effect on biological diversity. At the same time, when the availability of freshwater decreases, demand increases, resulting in disease and malnutrition in affected parts of the population. In July 2010, the right to water and sanitation was recognised by the UN General Assembly [35], and got focused as a global issue. Today, 2.2 billion people lack safe drinking water [36]. To ensure basic needs and low health risks, a person needs 50-100 litres of water per day [37]. This is known as *intermediate access* to drinking water by the World Health Organization (WHO). Statistics show that the average amount of household water used per day per person in Norway was 180 litres in 2020 [38]. This is nearly double of what is considered *optimal access*, 100 litres or more [37]. Based on this, it can be said that the awareness of water consumption among the population in Norway can be seen as low.

Goal 6 of the SDG reads "*Ensure availability and sustainable management of water and sanitation for all*" (Figure 2.3) [39].

Figure 2.3: *Goal 6 [39]*

§ Target 6.3: *By 2030, improve water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe re-use globally*

§ *Target 6.4: By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity*

The water used in households and for industrial purposes goes through an energy-intensive process in the form of treatment and distribution and cleaning, pumping and cleaning before it can be released back into the environment. After water, concrete is the second most used material [2][40]. Figures from 2012 show that concrete production represents 9% of global industrial water use. This constitutes approximately 1.7% of all freshwater that comes from surface and groundwater sources [41].

3 Knowledge Background

The knowledge background will present concrete as a material and current practice for recycling, washing and waste management at concrete mixing plants. As well as problem areas related to any water discharge from concrete mixing plants and the laws and regulations a plant needs to be in complains of.

3.1 Concrete

Concrete is a building material consisting of cement, aggregates, water and additives. NS-EN 206 [42] defines concrete as a "*material formed by mixing cement, coarse and fine aggregate and water, with or without the incorporation of admixture, additions of fibres, which develops its properties by hydration*". Ready-mixed concrete in this thesis seen as "*concrete delivered in a fresh state*" [42] by a producer, a ready-mix plant. Fresh concrete is "*concrete which is fully mixed and still in a condition that is capable of being compacted by the chosen method*" [42]. Table 3.1 shows how much of different materials are used in typical concrete:

Table 3.1: Typical content of concrete. Adapted from [43]

vol%	Content
40%	Coarse aggregates
25%	Fine aggregates
18%	Water
12%	Cement
4%	Air
1%	Additives

3.1.1 Aggregates

The properties of aggregate that is used in concrete are specified in NS-EN 12620 [44]. It includes natural, industrially produced and recycled materials. Aggregate is defined by NS-EN 206 [42] as "*natural, artificial, reclaimed or recycled granular mineral constituent suitable for use in concrete*". Further, a distinction is made between reclaimed and recycled aggregates. Reclaimed washed aggregate is "*aggregates gained by washing fresh concrete*", reclaimed crushed aggregate is "*aggregate gained by crushing hardened concrete that has not been previously used in construction*" and recycled aggregate is "*aggregate resulting from the processing of inorganic material previously used in construction*" [42].

National supplement Annex E in the concrete standard [42] recommends the use of aggregate specific to Norway. The classification and use of recycled aggregate can be seen in Tables NA.5, NA.6, NA.7 and NA.8 in the national supplement. Reclaimed aggregates from crushed hardened residual concrete from concrete mixing plants "*can be included with up to 5% within each of the fractions 0/4 mm and 4/32 mm in the production of new concrete. If only recovered crushed aggregate from residual concrete in fraction 4/32 mm is used, the proportion of recovered crushed aggregate can be included with 5% of the total aggregate amount of the concrete*" [42]. If more than the allowed 5% should be used, it is necessary to follow the specifications for recycled aggregate.

The aggregates impact concrete's mechanical strength and decrease the amount of water and cement needed. Therefore, the quality of the aggregate is essential. Granite and gabbro are known as good rocks for crushing to aggregate. Aggregate can also be made artificially, such as lightweight aggregate from expanded clay or be a residual product, such as slag. Particle size distribution is important when creating a mix design, as the smaller particles will fill in between larger particles.

Natural sand and gravel can be characterised as the most sought after aggregate for concrete. However, the demand for sand has led to overexploitation and degradation of sand deposits [45]. During the production of aggregate from granite, the process generates waste. As much as 50 % of the volume of produced aggregate production has been reported as waste [46]. The leftover dust can, for example, be utilised as sand replacement in concrete. At the same time, in the UK construction industry, the amount of aggregate from recycled sources is less than 25% [7].

3.1.2 Water

The quality of the water used in concrete follows specifications set by NS-EN 1008:2002 [47]. As long as the water quality is drinking water quality, it can be used in concrete without further testing. The amount of water used will impact the workability of fresh concrete and mechanical strength as the water is part of the cement hydration process [48].

3.1.3 Cement

The most common type of cement is Ordinary Portland Cement (OPC) [49]. It is defined in NS-EN 197-1 [50] as "*a hydraulic binder, i.e. a finely ground inorganic material which, when mixed with water, forms a paste which sets and hardens by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water*". The production process from raw material to finished product can be seen as a schematic representation in Figure 3.1.

Limestone is the main raw material for the production of cement and comes from quarries or mines. The materials are ground down to raw meal, a fine powder. It consists of about 90% calcium carbonate ($CaCO_3$), originating mainly from limestone. The remaining 10 % is silicon dioxide (silica (SiO_2)), aluminium (III) oxide (Al_2O_3) and iron (III) oxide (Fe_2O_3), originating from chemical corrective ingredients or mineral additives [43][51].

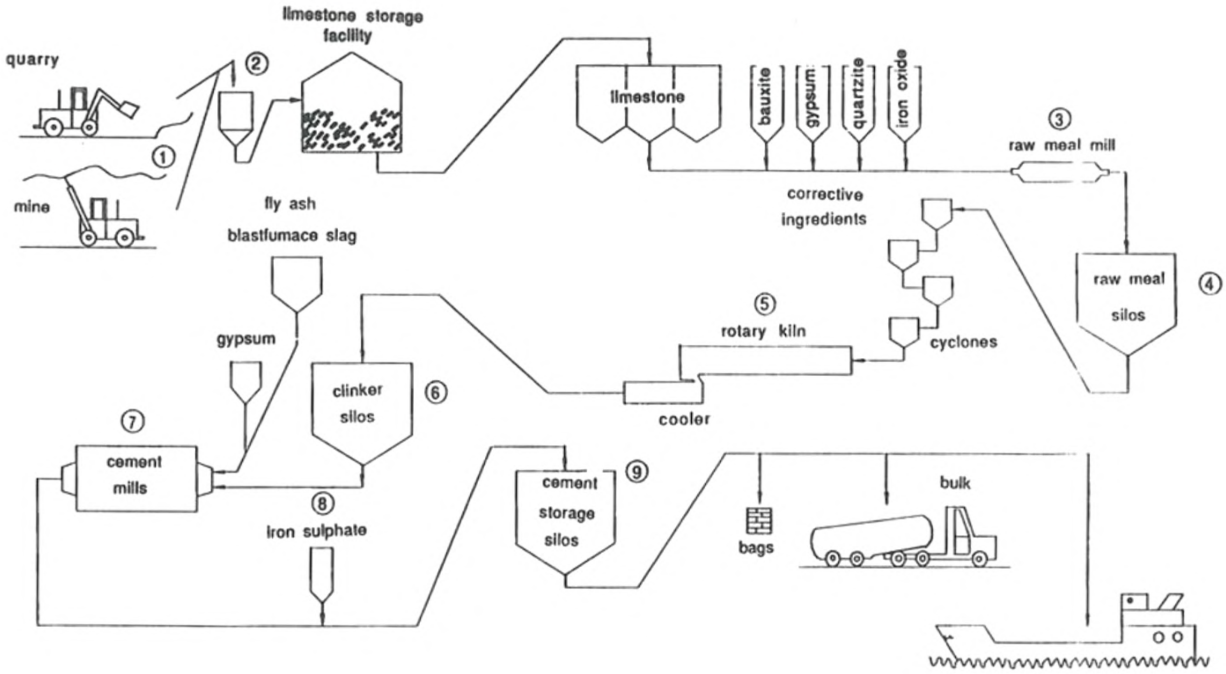


Figure 3.1: *Schematic representation of the production of cement [52]*

The raw meal gets heated at 800-1000°C in cyclone towers connected in series. The $CaCO_3$ is split calcium oxide (CaO) and CO_2, known as calcination, by the heat of the burning process [43][53]. Equation 3.1.1 shows the calcination process:

$$\underset{\text{calcium carbonate}}{CaCO_3} \xrightarrow{\text{heat}} \underset{\text{calcium oxide}}{CaO} + \underset{\text{carbon dioxide}}{CO_2} \tag{3.1.1}$$

When the raw meal enters the cylindrical rotary kilns, it gets exposed to different temperatures, up to 1450°C, before it is cooled down. The product looks now like solid pellets of 3-20 mm in size, known as clinker. Each tonne of clinker emits about 500 kg of CO_2 due to the splitting of $CaCO_3$ [54]. Cement consists of about 95% clinker. The remaining 5 % are materials that get added to achieve the desired properties of cement, such as gypsum, ferrous sulphate and mineral additions or supplementary cementitious materials (SCMs). The mix is then ground down to cement [43].

3.2 Recycling and Reuse of Concrete

Over the last 30-40 years, there has been focus and research on the recycling and re-use of hardened concrete that has been used for construction. On the other hand, recycling and re-use of fresh concrete residue and waste have gotten little focus [6][7]. Leftover products and waste at a ready-mixed concrete (RMC) plant can be divided into different categories [6]:

- Returned concrete waste (RCW): Fresh concrete waste that has not yet set. It can come from returning trucks before or after it has been at the customer due to over-ordering, something wrong with the workability or how it performed at the construction site, manufacturing trials and more.
- Concrete residuals within the concrete truck drum, portable mixers, plant mixers from normal production or after production testing.
- Hardened concrete waste (HCW): Hardened concrete returned from customers or from residue at the plant (inside drums, mixers etc.).
- Reclaimed aggregates: Coarse or fine aggregates regained by an aggregate reclaimer (washing-out) system.
- Wastewater: The wastewater that comes from cleaning mixers, truck drums and pumps or from reclaimer systems. The solids concentration of this type of water varies.
- Concrete sludge (slurry) (CS): The solids from the wastewater after sedimentation. In general, it has a water content from 150% and up. If the CS is dewatered through a filter press, the water content is reduced and can come down to 100% or lower. An example of CS can be seen in Figure 3.2.
- Reclaimed water: The water that has gone through a dewatering process.

(a) *Wet CS that has sedimented and then is shovelled up again. The wastewater can bee seen in the top left*

(b) *Semi dry CS*

(c) *The semi dry CS can be easily squashed with your fingers*

Figure 3.2: *Concrete sludge at Ribe Betong*

There will always be some returned concrete, as it is normal for buyers to have a safety margin for the concrete needed for a cast. However, miscalculations can also occur, especially from private customers. Table 3.2 gives an overview of the amount of RCW from overall production in different regions.

Table 3.2: *Level of returned fresh concrete waste by weight. Based on Table 1 in [6]*

Countries/regions	Average Level	Range and Reference
Italy	1.4%	0.9-1.8% [55]
Japan	1.5%	1.0-2.0% [56]
Hong Kong	1.5%	≈1.5% [57]
Denmark	2.0%	1.0-4.0% [58]
Europe	2.5%	1.0-4.0% [59]
Mauritius	2.5%	1.0-4.0% [60]
USA	6.0%	2.0-10% [61]
Brazil	9.0%	≈9.0% [62]

Historically, it has been used as fill material or dumped in landfills [6][7][63], or just in the sea [64]. It is an environmental and economic concern that a large amount of produced concrete never is used and becomes waste. It has become more and more common lately to use this to make concrete products, such as blocks for non-construction purposes (see Figure 3.3 for illustration) [6]. If a larger amount of RCW is returned, it can also be used "as is" for a new customer if the plant has an order that fits. An admixture system of stabiliser and activator can be used to prolong the time span for re-use of RCW. The stabiliser stops the cement hydration process for up to 72 hours, and the activator reactivates the process when the RCW is to be used [65]. According to the findings of Paolini and Khurana [65], the properties of concrete were not affected unfavourably in either fresh or hardened state when utilising stabiliser and activator admixtures.

(a) Concrete blocks [66]

(b) Production of blocks [67]

Figure 3.3: Concrete blocks for non-construction purpose

3.3 Concrete Cleaning and Wast Management

3.3.1 Waste Management

Wang and Zhang [68] divided concrete waste management into four methods (see Figure 3.4):

1. Everything is discharged for hardening and goes to landfills or is used as filling materials for land reclamation
2. RCW gets blended directly in the next batch as a partially hydrated cementitious material. This can speed up setting and hardening time. item Super absorbent polymers are used to make a granular material that can be used as aggregate in new concrete
3. Reclaiming systems

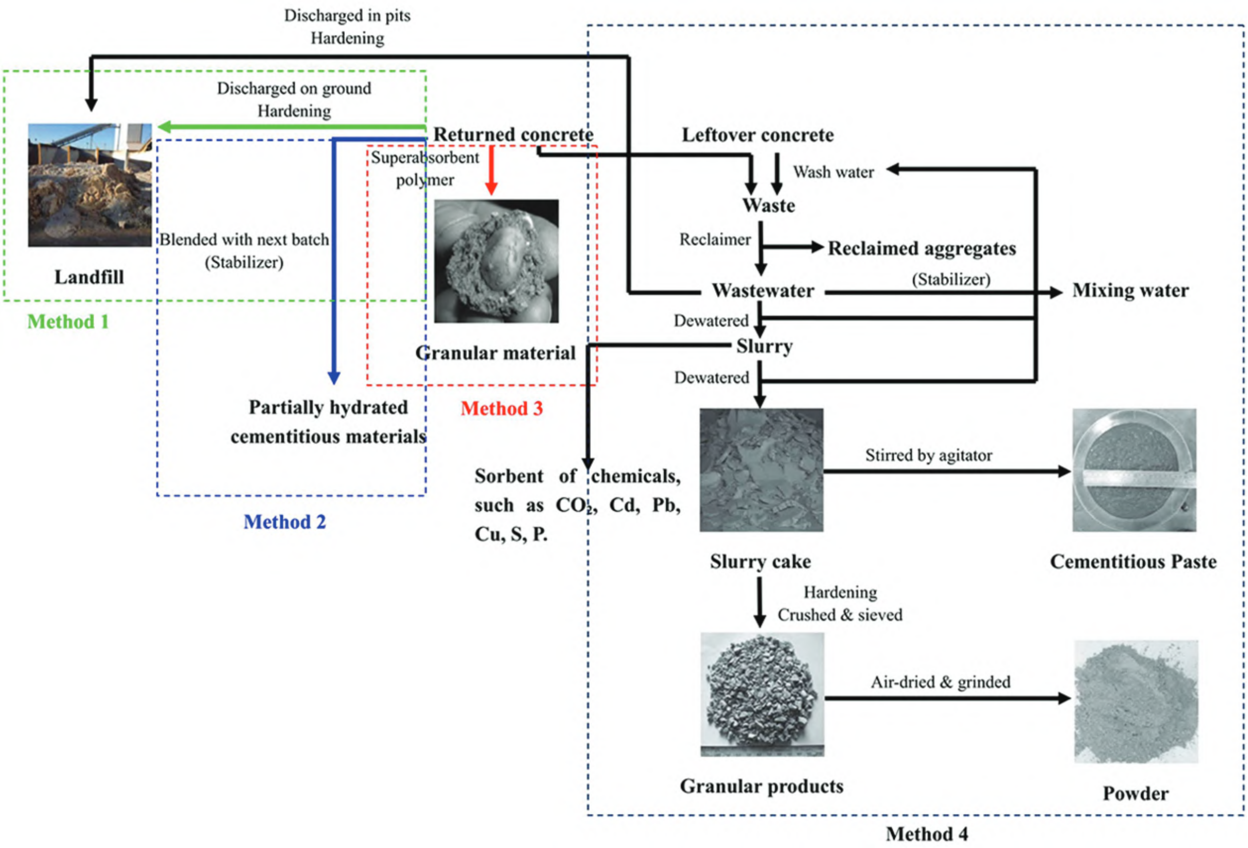


Figure 3.4: *Management of fresh concrete waste [68]*

The wastewater and concrete slurry comes from the cleaning of equipment. In a truck drum, it can be about 250 to 350 kg of residue concrete left on the interior [65][68]. It is estimated that the quantity of yield concrete sludge in the world each year is between 165 and 330 million tonnes (2011) [69]. Under follows different cleaning methods for concrete truck drums.

3.3.2 Washing with Water

The norm in Norway and many other countries today is to clean concrete truck drums with water after use. The drum gets filled with water while turning around, and it has been reported that 3000 litres of water is used in the UK [7]. Paolini and Khurana [65] reported about 1500 litres of water needed to wash one truck drum with concrete residue. The washing water is often poured into sedimentation basins (see Figure 3.5).

Figure 3.5: *Sedimentation basins for concrete slurry and washing water*

3.3.3 Washing with High-Pressure Water System

High-pressure robotic systems are made to wash inside truck drums. See Figure 3.6 for schematic overview. They were developed to ensure no need for manual labour inside the drums with jackhammers to remove hardened concrete residue. It runs on diesel [70][71]. A high pressure, fully automated system, very similar to the previous one, can be used for daily cleaning [72]. It runs on electricity, and the producers claim a 90 % reduction in the hardened concrete build-up [73].

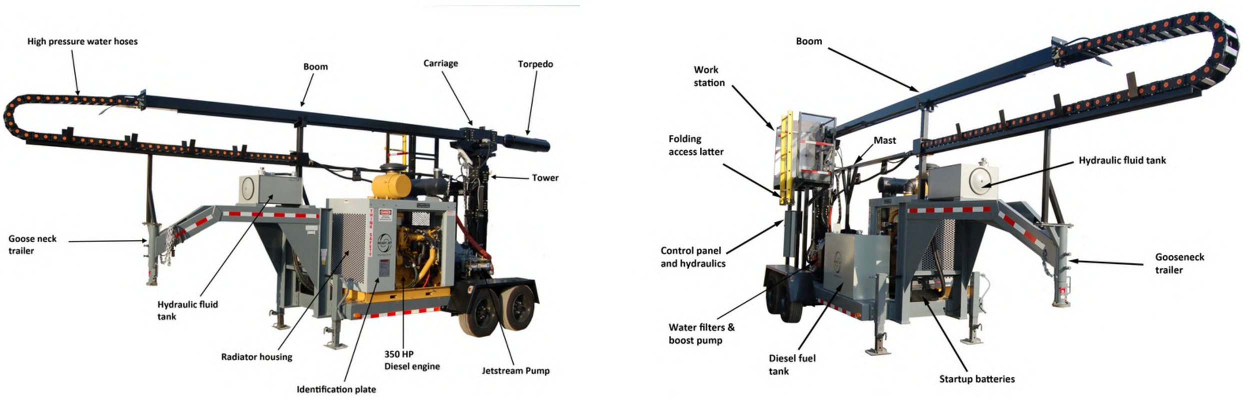


Figure 3.6: *High pressure system for removing hardened concrete build up [70]*

Figure 3.7: *The robotic high pressure lance for daily cleaning [73]*

3.3.4 Washing with Water and Aggregate

This method of washing is known as stoning out, and according to Sealey, Phillips and Hill [7], 2 tonnes of coarse aggregate and 200 litres of water is typically used in the United Kingdom for this washing procedure. The drum is driven four or five times out to the point of discharge before it is discharged into the aggregate stockpile or kept in the truck drum until the next day. The aggregates can then be used in a new batch of concrete [7].

3.3.5 Reclaimer System for Re-use of Aggregates

A concrete reclaimer can separate and reclaim the aggregates and sand from the returned concrete, and concrete residuals within the concrete truck drum [7][63][68]]. The reclaimer can be thought of as a simple system which uses water to rinse aggregates after the washing procedure of concrete drums and mixers. However, it requires considerable investment, careful maintenance, and management to ensure reliable operation [7]. The system normally has two to three sedimentation basins [68]. In addition to the reclaim system, as illustrated in Figure 3.8, a filter press can be added to the system at a concrete producer to remove water from the sludge. For example, Velde is a Norwegian supplier of crushed stone, asphalt, concrete and recycled products [74]. They have a factory sized reclaimer system with a filter press. An independent research institute, Sintef, found that the system can remove 60-80 % of the water in the sludge [75].

If the coarse aggregate is reclaimed, it can be used on equal terms to virgin aggregate. The wastewater can be used continuously as washing water or as mixing water if in compliance with the requirements in current standards. Tap water can be mixed with it to meet the requirements [68]. The review done by Wang and Zhang [68] found that the processed slurry could be used as a binder in blocks or mortar. Due to the alkalinity and the content of calcium in the sludge, it could be used as a chemical sorbent for water clarification, phosphorus adsorbent, an agent for desulphuring, and in the production of calcium carbonate as a CO_2 capturer. It can also be used in road construction as a soil stabiliser at the base of the road, filler in concrete, geopolymer and glass ceramics, or fine aggregate in new concrete or if combined with a granulation procedure to make coarse aggregates [68].

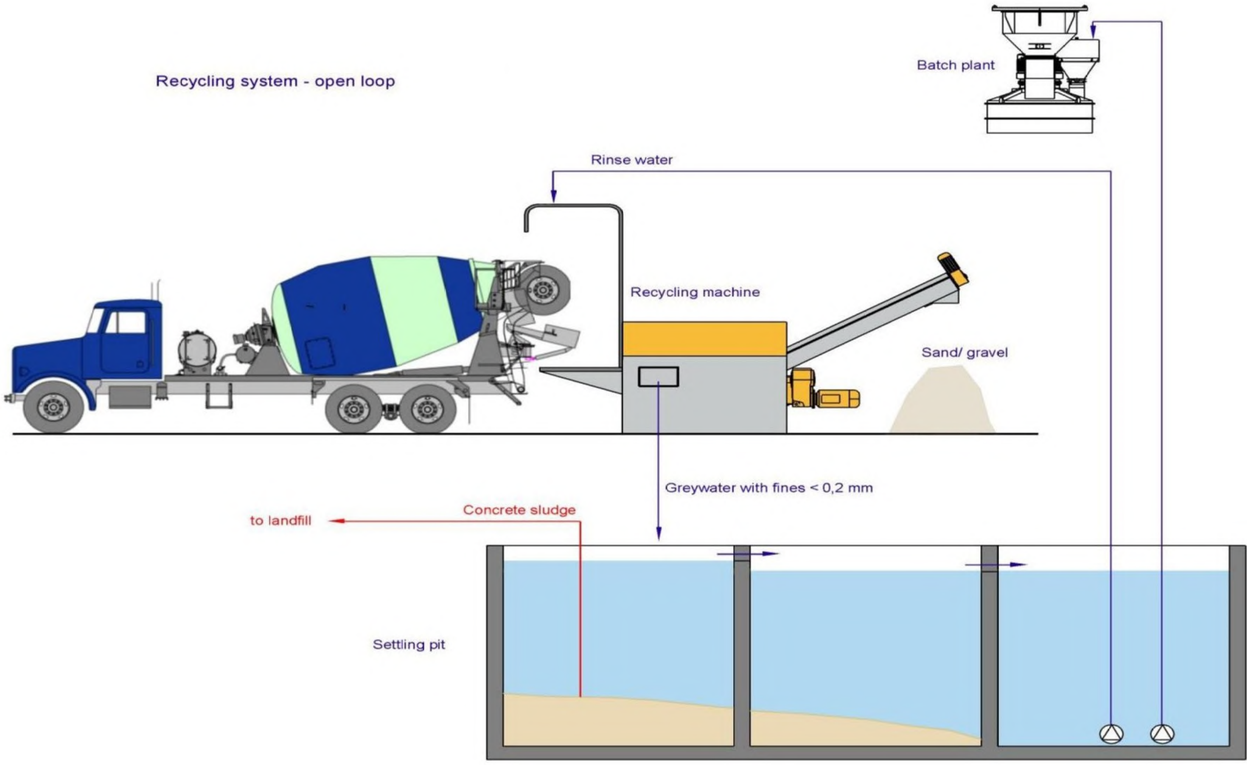


Figure 3.8: *Basic concrete reclaim system [76]*

3.3.6 Dry Washing with Two-Component Powder

Superabsorbent polymers that are reported to be nontoxic additives [68] can be used for washing and reclaiming. Re-Con Zero (RCZ) [77] is such a product. The two components are a water absorber and a solidification accelerator that turns into dry granulate when mixed with concrete. The amount of returned concrete in a drum will wary, and at once, it can be used for up to 3 m^3 RCW. After the procedure, fine sand containing about 20 % of fines, particles < 0.125 mm, is left in the drum. The granulate can be re-used for dry washing as well as go into new concrete production as aggregates [78]. The fines can be used as filler or recycled as fine sand. From 1 m^3 RCW, it generates 2.2 tonnes of recyclable aggregate [77]. The product is reported to decrease the amount of concrete sludge by 70-80% [79][80], and the producers claim that if compared to disposing of RCW in landfills, their process saves up to 40 times the CO_2 produced [81]. Figure 3.9 shows the process of dry washing with Re-Con Zero as well as the outputs of the process.

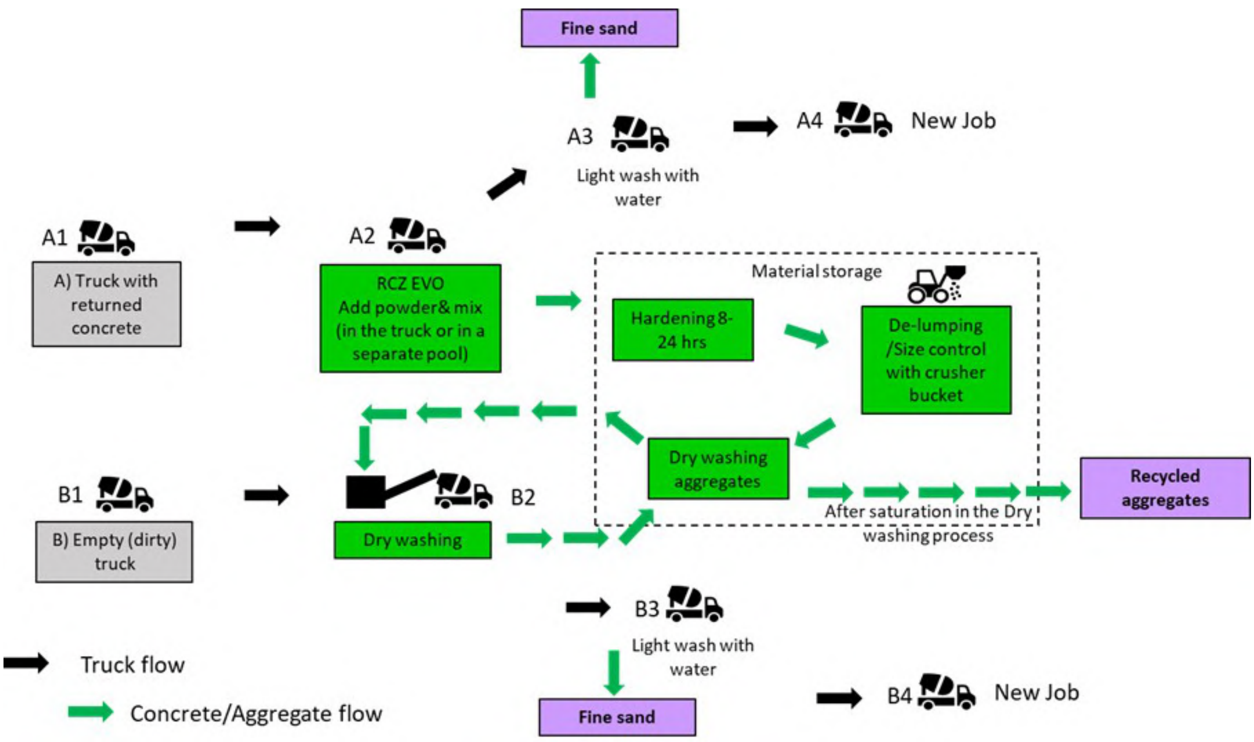


Figure 3.9: *Washing process with Re-Con Zero [82]*

3.4 Type of Pollution and its Effect on Nature

As described in Chapter 3.2, there are several categories of leftover products and waste at a ready-mix plant. This sub-chapter describes the components that Ribe Betong are focused on that are problematic if released to nature from their concrete waste.

3.4.1 Suspended Solids

Suspended solids are the term for the water content of suspended, particulate solids. There can be both things that can sediment and float. It depends on how much is in the water to what impact it has on the recipient and those who live there [83][84][85]. See Table 3.3 for effect on fish in fresh water.

Table 3.3: *Suspended solids in water and their effect on fish [83]*

Suspended solids	Effect
<25 mg/l	No harmful effect
25-80 mg/l	Good to medium good fishing. Somewhat reduced return.
80-400 mg/l	Significantly reduced fishing
>400 mg/l	Very poor fishing, greatly reduced yield

When there are high concentrations of suspended solids released into a harbour or a fjord, sludge on the bottom and on those who live there may occur. If there is a lot of fines in the water that is realised, the particles can float up and affect the fish that live there. This is even with discharges at

20 m water depth [83][84][85]. Suspended solids can be removed by sedimentation and flocculation of what floats to make it sediment and utilising filtration.

3.4.2 pH

Aquatic organisms can be affected by variations in pH. Species richness tends to drop at both ends of the pH scale. On a general basis, the pH of fresh water should not be lower than 6 or higher than 8.5. Seawater generally has a very high buffer capacity. This means that traditionally it has been thought that if water with a high pH is sent out to a deep enough depth, things will go well. Wash water with pH, e.g. 12 must be diluted 1000 times before it reaches the seawater background level, while carbonated wash water with pH 10 only needs to be diluted 10 times. This is because the pH scale is logarithmic.

Table 3.4: *pH effect on freshwater fish [86]*

pH	**Effect on fish**
5-9	Normally no harmful effects
9.0-9.5	Probably harmful to salmon and perch over prolonged exposure.
9.5-10.0	Lethal to salmon over prolonged exposure. The fish are resistant to such pH values for short periods. It may be harmful to the developmental stages of some fish species
10.0-10.5	Salmon and roaches may be resistant to such pH values for short periods, but the fish die from prolonged exposure
10-5-11.0	Salmon die in a short time. Prolonged exposure means that carp, pike, goldfish and tench also die.
11.0-11.5	All fish species die in a short time.

High pH can be adjusted with acid. This requires the handling of acid, which is a health and safety risk. It can also release harmful sulphates and chlorides into aquatic environments. Or carbon dioxide can be used to lower the pH value in water. Carbon dioxide can be recovered from other processes. When using carbon dioxide, the pH value will drop more gradually and end up below 6, even if overdosed. As carbon dioxide is a weak acid, the pH value drops more gradually than in mineral acids, and thus it is easier to make thorough checks.

3.4.3 Chromium VI

Chromium I is one of chromium's forms that can occur under high pH and high levels of oxygen. Limestone has a naturally high content of chromium oxide. The chromium will, under the production of cement oxidised to chromium VI. Some of the chromium VI in cement comes from fuel and residues from the grinding process. Reducing agents (for example, ferrous sulphate) are often added to keep the level in check. The regulations state that cement must not contain more than 2 mg of soluble chromium VI per kg of dry cement. Chromium VI compounds are highly toxic and have long-term effects on aquatic life. For humans, it can damage genetic material and reproduction and increase the risk of cancer and allergies. Chromium III compounds are generally less toxic [87][88][89].

Chromium VI is very soluble at all pH. Chromium III is less soluble and will precipitate at pH 7-10. So there is an equilibrium between them that gets affected by changes in pH. A shift of the equilibrium from chromium III to chromium VI happens when the pH increases and vice versa when the pH sinks [88].

To get rid of it in your process water, as long as the chromium VI is bound to particles, it can be removed from the water by sedimentation. You can adjust the pH, between 6 and 9, and then have a sedimentation step after this. This will prevent precipitated Chromium 3 from being released and reoxidised in the recipient. Chromium VI in water from hardened concrete was found by the Norwegian Geotechnical Institute (NGI) in 2020 to be changed into chromium III when in contact with soil. The chromium III binds to the organic matter in the soil, which stops the further spread of chromium from the concrete water [89].

3.5 Regulations, Standards and Guidelines

To ensure high quality, consistency and safe production and use of construction materials and work, standards are established. By regulating and ensuring the documentation of technical specifications, miscommunications and misinformation is also reduced. The International Organization for Standardization (ISO) is the international organisation that the regional, as the European standardisation organisation CEN, and national organisations often follow. Standards Norway establishes and publishes NS-EN - standards that contain methods and guidance that comply with Norwegian law [90]. Standards can be defined as a "document, established by consensus and approved by a recognised body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context" [91].

Standards can be seen as necessary and practical. However, the standards can be seen as rigid when it comes to innovative and novel solutions. As adoptions and new standards need to undergo several stages involving numerous parties, approval of the standards is a tedious process that can be impossible and result in limitations, especially towards adaption toward local challenges. McDonough and Braungart [92] see regulations as "something to be redesigned". This can be interpreted to that where regulations need to be put in place, there is an opportunity and potential for improvement [92].

Ready-mix concrete producers need to comply with these laws and regulations [93] (translated by the author):

- "*Act on protection against pollution and on waste (the Pollution Control Act) § 7 on the duty to avoid pollution*"
- "*The Pollution Control Act § 32 on the handling of industrial waste*"
- "*Regulations on recycling and treatment of waste (Waste Regulations) Chapter 9 on landfilling of waste, § 9-2 second paragraph*"
- "*Regulations on recycling and treatment of waste (Waste Regulations) Chapter 11 on hazardous waste*"
- "*Regulations on systematic health, environment and safety work in enterprises (Internal Control Regulations) § 4 on the duty to internal control, § 5 on the content and documentation of internal control systems*"

In 2016, there was a national action where the county governor visited businesses in the mineral industry - cement, concrete and non-metallic mineral products sector. The authorities aimed to identify whether the industry needed its own permit under the Pollution Control Act in regards to emission control, internal control, and waste management [93]. The county governor in Oslo and Akershus did consider these points as environmental problems that may be related to concrete production when they performed the audits [94]:

- "*Discharge of particles into water which can cause siltation of watercourses*"
- "*Discharge of washing water containing chemicals and heavy metals*"
- "*Emissions of environmentally hazardous substances from hazardous waste that are not handled properly*"
- "*Discharge of plastic reinforcement in washing water or overflow from sedimentation basin and diversion basins*"
- "*Emissions of dust into the air which may give rise to hazardous levels of particulate matter*"
- "*Illegal disposal of sludge containing environmental toxins and plastic reinforcement*"

Construction materials used in the construction industry are regulated by the technical requirements for construction works (TEK17) [95]. Environmental requirements are not quantified, but indications are given that the production of materials should be carried out in the interests of energy accountability. This can be seen as a means to steer the industry toward sustainable solutions.

Governmental tendering processes emphasise social responsibility in their criteria and the Procurement Act [96] further sets requirements for safeguarding environmental conditions [97]. Private builders and contractors also establish environmental requirements in their bidding processes and contracts. Moreover, building certification systems have had a positive impact on the construction industry's drive towards environmental responsibility and the need for sustainable innovation and technological solutions.

Norwegian Concrete Association published in 2015 (revised in 2019 and updated in 2020) a publication on low carbon concrete. It has become a reference document for the industry when dealing with projects that should be environmentally responsible or that require greenhouse gas emission limits [98]. Table 3.5 shows the different low carbon classes and the associated maximum level of CO_2 emissions. The industry uses them to know how much CO_2 is related to different types of concrete and uses, for example, these figures when planning for environmentally certified projects.

Table 3.5: *Low carbon concrete classes with the limit values for greenhouse gas emissions [kg CO_2-equ. pr m^3 concrete] from cradle to gate (A1-A3 and NS-EN 15804:2012+A2:2019/7/). The table is translated by the author and adapted from Table 1 in [98]*

Strength classes[1] and low carbon classes	**B20**	**B25**	**B30**	**B35**	**B45**	**B55**	**B65**
Industry Reference (numbers from 2019)	240	260	280	330	360	370	380
Low Carbon B	190	210	230	280	290	300	310
Low Carbon A	170	180	200	210	220	230	240
Low Carbon Plus[2]			150	160	170	180	190
Low Carbon Extreme[2]			110	120	130	140	150

1) See [98] for the relationship between strength classes, durability classes and carbon classes
2) Possible level for some projects, but with several limitations in the standard work, and limited availability. Feasibility must be clarified in each individual project

4 | Research Question

This thesis looks at concrete producers with a focus on the sustainability profile of concrete production. The research question with sub-questions are as follows:

How can the concrete industry improve its sustainability profile with the re-use of surplus fresh concrete and its by-products?

- How can dry washing of concrete truck drums influence the possible use of reclaimed aggregate?
- What are the environmental effects of dry washing?
- How does the wastewater from the ready-mix concrete plant impact the environment if it is discharged?
- How do regulations and standards affect the use of surplus fresh concrete and concrete by-products in the construction industry?

This thesis does not focus on solutions for recycling and re-use of concrete waste outside the concrete manufacturer's domain.

5 | Case

5.1 Case Study

A case study can be thought of as a way to collect data and information about a phenomenon, as well as a way to describe and understand it [99]. When asking "why" or "how" in a research question, Yin [100] says a case study is a good approach because it examines the case thoroughly and sets it in context with the real world. However, when a case is used as a method to study how things are, it is important to keep in mind that the case in question may not be representative of an entire group and that generalisations of a group are therefore difficult to achieve [99]. This thesis uses Ribe Betong as a case study as an example of how a ready-mix concrete plant is run in Norway today and for the collection of data.

5.2 Ribe Betong

Ribe Betong was founded in 2005 and is today one of Sørlandet's largest ready-mix concrete producers with seven production lines [101]. The concrete plants are located in Kristiansand, Arendal, Lillesand, Lyngdal, Flekkefjord and Åseral. Ribe Betong produced a total of 221 257 m^3 fresh concrete [102] and 6131 m^3 concrete blocks (by-product) for non-construction purposes [103] in 2021 (see Table 5.1).

Table 5.1: *Production numbers at Ribe Betong in 2021. *No data [102][103]*

Production line	Fresh Concrete	Ribe Blokk	Unit
Lyngdal	15 102.60	164.43	m^3
Flekkefjord	10 832.88	154.72	m^3
Åseral	12 512.98	*	
Lillesand	30 805.09	1 407.71	m^3
Kristiansand	122 426.60	3 581.62	m^3
Arendal	29 576.84	822.13	m^3
Total	221 256.99	6 130.60	m^3

The concrete produced varies from standard, low carbon, lightweight and special concrete. About 40% of the produced concrete is of strength class B30. When the firm has much delivery for road projects, a large amount of B45 concrete is also produced. The average slumpe of all concrete produced is 200 mm [104]. Figure 5.1 shows the total production volume at the different production lines. The stations are spread around the region, enabling Ribe Betong to be close to their customers [105]. The company has 120 employees, 42 concrete trucks, 28 pumis (combi truck and pump) and

12 trucks for raw material transportation (see Figure 5.1 for illustration of concrete vehicles) [101]. The company is NS-EN ISO 14001 [106] certified and focuses on re-use and resource utilisation of their materials and residual materials according to their website [105]. All production facilities are NS-EN 206 [42] approved [105]. All ready-mix concrete sold has an environmental product declaration (EPD) [105].

(a) *Concrete truck*

(b) *Pump*

(c) *Pumi*

Figure 5.1: *Delivery equipment for concrete*

Figure 5.2 shows an overview of the area where Ribe Betong's production line is located in Kristiansand. The picture shows the two mixing plants with associated binder silos, aggregate storage, washing area, sedimentation basins, and storage basins for waste concrete, among other things.

Figure 5.2: *Overview of Ribe Betongs production line in Kristiansand. Foto: A. Verma [107]*

In the 1980s, fresh concrete residues and washing water was typically let straight out to the sea from the concrete producers that lay on the coast of Sørlandet [64]. During the 1990s, the nationwide industry organisation, the Norwegian Concrete Factory Association FABEKO, developed and published a guide to how to build sedimentation basins [108]. Hardened concrete and dried sludge from the first basin could still be discharged into the sea. Sludge from basin two got collected by Septic services two to three times a year.

In the 2000s, things started to change as Sintef published a report regarding the problem of hardening concrete residues, sludge and wastewater after washing. The report concluded that what is left of residues from concrete production is considered "pure masses" and that water from washing should be used back for production. During this time, Ribe Betong starts to use fresh residual concrete to produce concrete blocks. In some cases, the hardened concrete is crushed down to aggregates and used in concrete blocks. During the 2010s, concrete waste was seen as "lightly contaminated masses", and in 2017 chromium VI is considered a problem and aliphates (comes from formwork oil or diesel). From now on, Ribe starts systematic monitoring and sampling of sludge and discharge water [64].

At Ribe Betong today, sedimentation basins are used, and there is a system that re-uses water to wash the concrete truck drums. First, water gets poured into the drum from above. The delicate wash afterwards is carried out by regular handheld high-pressure washers. Ribe Betong estimates the water use to be about 2 m^3 to wash a mixer, 1 m^3 to wash a concrete drum, about 1 m^3 to wash a pump and about 1.5 m^3 to wash a pumi (combi pump and concrete truck) when it has had a load of concrete inside its drum [109]. Sometimes a pumi only uses the pump part as the concrete is delivered by a concrete truck to the location of the pumi. The equipment is washed daily or more often if needed.

The next page presents a schematic representation of Ribe Betong's production system (Figure 5.3). It shows all processes at or by Ribe Betong (within the blue area) and associated processes, products, by-products, and waste. From the top left, we can follow how materials, energy, and transport lead together to ready-mixed concrete and how the residual concrete is treated when returning from the construction site. On the right side follows the process for the blocks produced from residual concrete. The mixing plant itself, the building of it and building materials as well as maintenance have not been included, nor have the inventory of machines and vehicles.

A returning concrete truck can either contain surplus fresh concrete (RCW) or be empty with a thin concrete residue film when it returns to the plant. If the truck contains RCW, the RCW is used to produce Ribe Blokks, which are sold as a by-product. If there are no forms available, the RCW can be discharged into storing areas where it will harden and end up as filling material or in landfills. Ether the drum is empty or contains RCW, it will have a thin residue film inside. This is washed away with water. The system utilises water from the settling (sedimentation) basins and clean water from the municipal water supply (drinking water). The washing water is then discharged into the settling basin, which consists of 3 consecutive basins. The basins for sedimentation need to be emptied for sludge. The sludge is then let to dry in storage areas. Suppose the sedimentation basins become overfilled, for example, with frequent use or large precipitation amounts. In that case, the basins will be overfilled, and washing water will overflow to the sump before a new overflow to the municipal surface water pipe, which ends in a stream. A hardened concrete build-up will occur if the concrete drums are not cleaned thoroughly and frequently enough. This requires manual jack hammer work before it can be discharged into the storage area for hardened concrete waste.

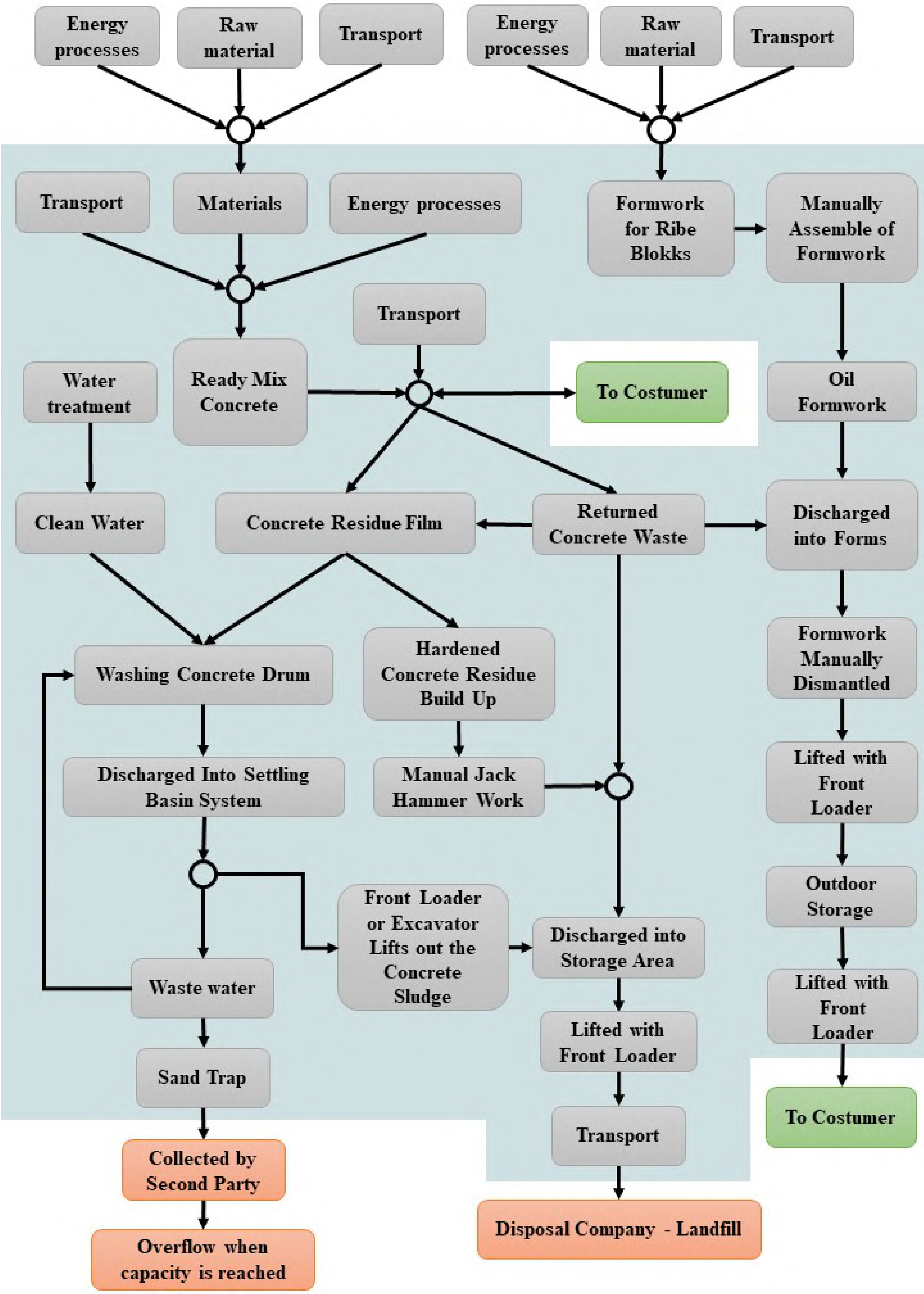


Figure 5.3: *Schematic representation of the production system at Ribe Betong*

5.2.1 Returned Concrete Waste

Ribe Betong had in 2021 2.8% returned concrete waste. The different production lines vary in the amount of RCW they have. Table 5.3 shows the difference. Below follows Table 5.2 with the amount of by-product and concrete waste at Ribe Betong in 2021 and Table 5.3 with a percentage overview in relation to the amount of concrete produced. The abbreviations in the tables below stand for: RCW = Returned concrete waste, HCW = Hardened concrete waste, CS = Concrete slurry and Combined = RCW, HCW and CS

Table 5.2: *Production numbers at Ribe Betong in 2021 for fresh concrete and RCW. RCW is based on the production of by-product Ribe Blokk [102][103]*

Productionline	Concrete	Ribe Blokk (RCW)	HCW	CS	Combined	Unit
Lyngdal	15102.60	164.43		45658.00	165.68	m^3
Flekkefjord	10832.88	154.72		90.00	244.72	m^3
Åseral	12512.98		272.00		272.00	m^3
Lillesand	30805.09	1407.71	867.00	1000.85	3275.56	m^3
Kristiansand	122426.60	3581.62	3470.50	2915.00	9967.12	m^3
Arendal	29576.84	822.13		24.00	846.13	m^3
Total	221256.99	6130.60	4609.50	4031.10	14771.2	m^3

Table 5.3: *Amount of by-product and waste at Ribe Betong in 2021 [102][103]*

Productionline	RCW	HCW	CS	HCW & CS	Combined	Unit
Lyngdal	1.1		0.01	0.01	1.1	%
Flekkefjord	1.4		0.8	0.8	2.3	%
Åseral		2.2		2.2	2.2	%
Lillesand	4.6	2.8	3.3	6.1	10.6	%
Kristiansand	2.9	2.8	2.4	5.2	8.1	%
Arendal	2.8		0.1	0.1	2.9	%
Total	2.8	2.1	1.8	3.9	6.7	%

6 | Method

The method for this master's thesis is a combination of life cycle assessment, empirical work and a litterateur review.

6.1 Life Cycle Assessment

Life cycle assessment (LCA) was used to evaluate the environmental effects of Ribe Betong's concrete plant. The LCA identifies, calculates and evaluates the environmental impacts of a process, service or product. The method is holistic as it looks at the whole system and ensures that improper optimisation of components is avoided [110]. In other words, a comprehensive overview of all environmental impacts is created, and it outlines the resources used and released emissions at every phase of the process [111]. The process, service or product undergoes a thorough "cradle to grave" analysis [110][112].

The International Standard 14040 [113] structures the methodology used for the life cycle assessment. The standard [113] defines LCA as a "*compilation and evaluation of the inputs, outputs and the potential environmental impact of a product system throughout its life cycle*". The method has four phases [114][115]:

1. Goal and scope definition - defining the system and system boundaries
2. Inventory analysis - the study of energy and material flow
3. Impact assessment - potential environmental impacts are assessed
4. Interpretation - gives understanding and help towards informed decisions

The four phases are interlinked, as is illustrated in Figure 6.1 and can be described as an iterative process in which calculations and assumptions must be evaluated when new information or outcomes occur [110][115].

There are two general categories of LCA studies, attributional and consequential. An attributional study is a material balance approach and focuses on the complete system of a product and all environmental lodes that come from the specific product. A consequential study looks into how changes can be made by influencing the system, so it expands the study boundaries to look at possible consequences [115][116]. In other words, it can be seen as two different agendas, "what do we have" and "what if we". This LCA study is attributional as it looks at the process today at Ribe Betong and how it affects its surroundings and the environment.

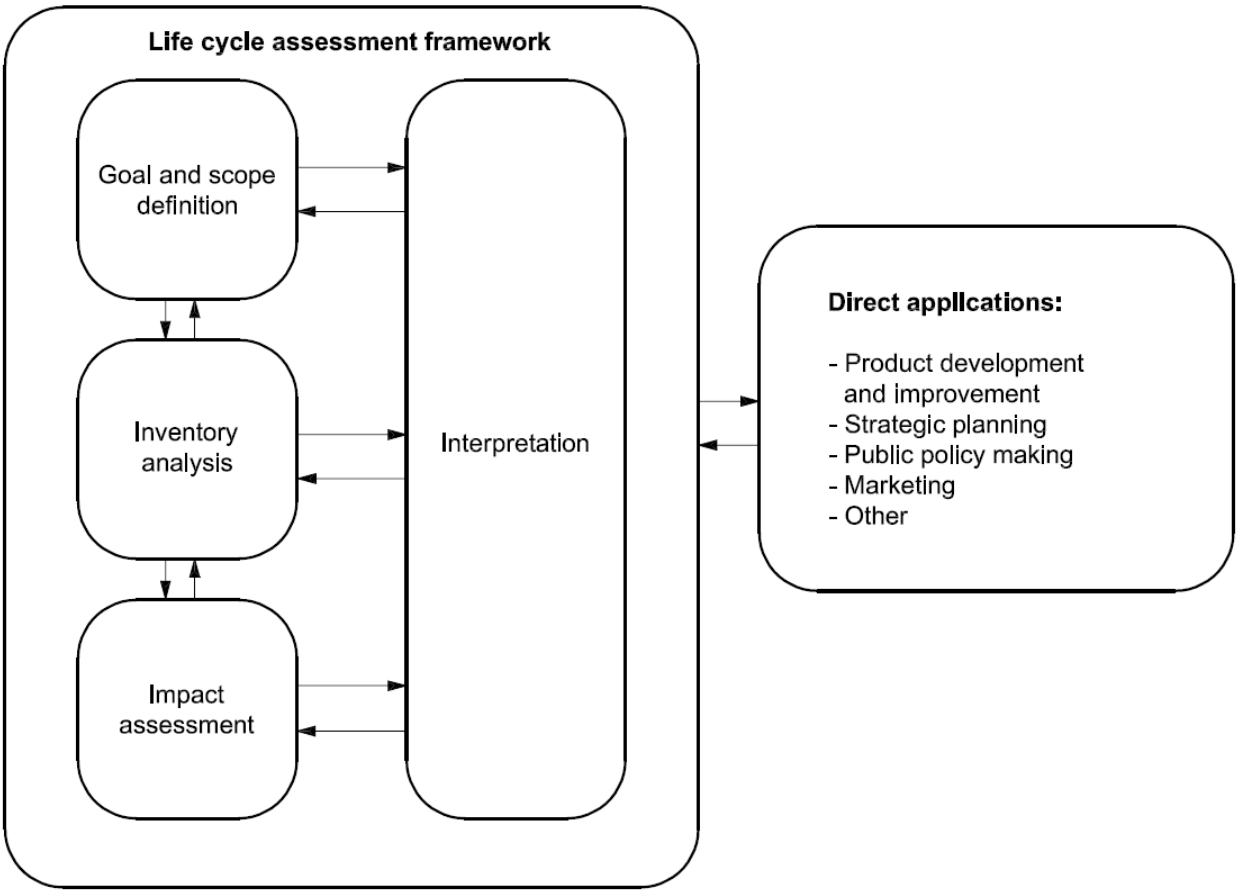


Figure 6.1: *The stages of an LCA [113]*

6.1.1 Goal and Scope Definition

The goal and scope definition phase includes establishing the functional unit, defining the system and system boundaries, and establishing data quality criteria [113][114][117]. Below follows Figure 6.2 that shows what is typically included when performing a cradle-to-cradle, cradle-to-grave and cradle-to-gate LCA of concrete production. Cradle-to-gate is an analysis of only the production of concrete. It does not include service life (use) and end of life (waste treatment) [110]. Cradle-to-grave and cradle-to-cradle incorporate the whole life cycle of a scenario or a product [118]. Cradle-to-grave focuses on using the inputs only one-time [92]. It can be described as a downcycling concept where the material at the end of life stage is disposed of, and its usability is then seen as "*an application of less value than the original purpose of the material*" [119]. In comparison, cradle-to-cradle includes re-use and recycling of the material in the system [118].

In addition, to illustrate the three different variants of assessment, Figure 6.2 shows how the different material processes, their stages and where energy inputs are needed. It also displays that emissions from concrete production happen throughout the whole life cycle of concrete. Waste from other sources can be included in the system as a resource, such as fly ash, silica fume, and ground granulated blast furnace slag (GGBFS).

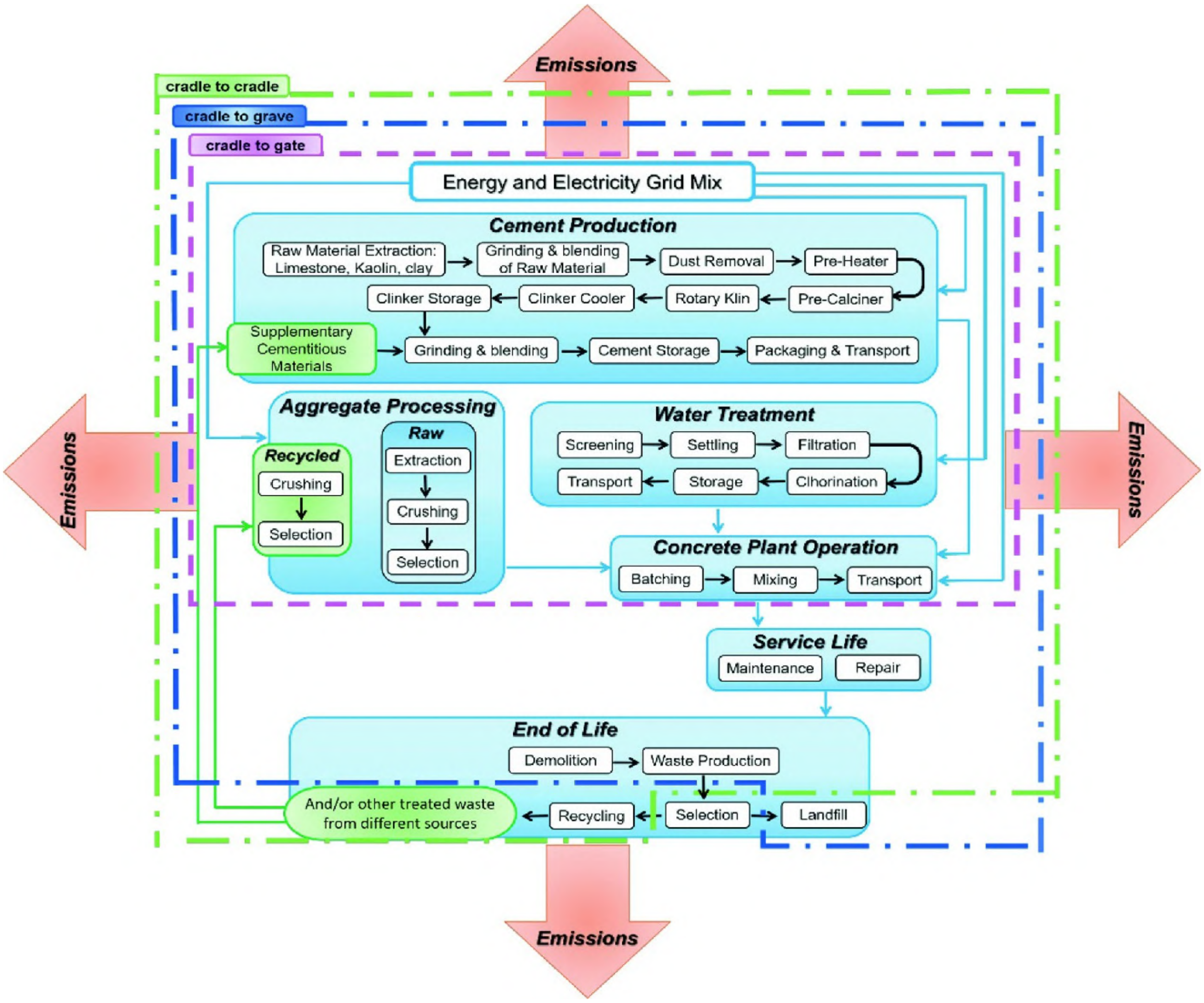


Figure 6.2: *Cradle-to-cradle, cradle-to-grave and cradle-to-gate of concrete [120]*

The goal of the LCA is to compile and evaluate the environmental consequences Ribe Betong's production of concrete has on the environment. This is to see if anything can be changed to improve Ribe Betong's process and its sustainability profile. The findings can be used for product improvement, strategic planning, decision-making, or marketing by Ribe Betong. The functional unit is set to 1 m^3 of produced fresh concrete in 2021. 1 m^3 of concrete is defined to 2350 kg.

System Boundaries

The information obtained through the inventory analysis defines the exact details for the boundaries [110]. Figure 6.2 was used as a guideline when defining the system boundaries. The system boundaries can be seen as cradle-to-grave, as the sludge and hardened concrete does not get re-used. Figure 6.3 shows the system boundaries (marked by a dotted line). They are limited to the available information. See Chapter 5 for further information about the processes in the system. The geographical boundaries are the origin of raw materials and the production location of the raw materials. Further, it includes the Kristiansand area where Ribe Betong sells their concrete produced at the production line in Kristiansand.

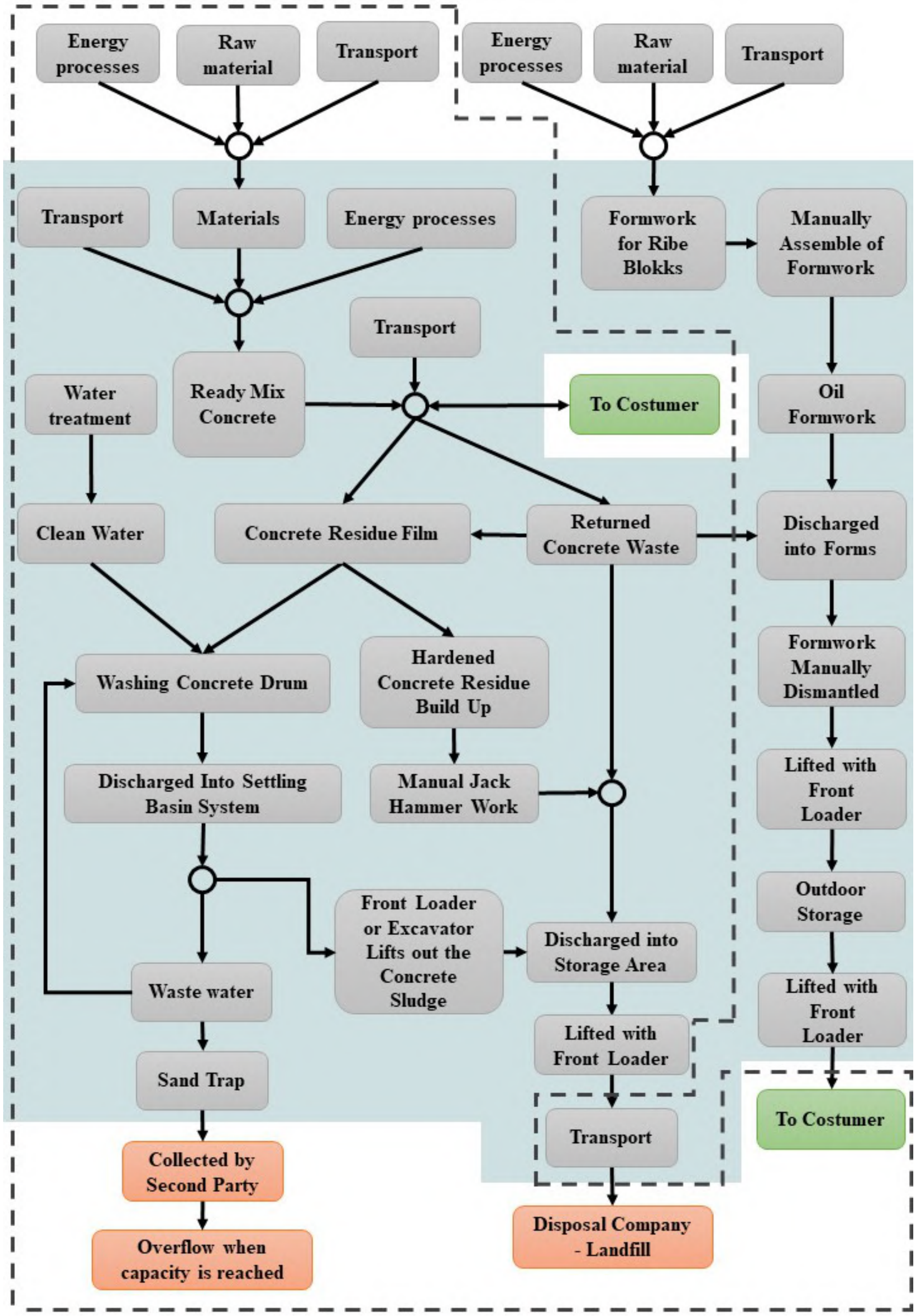


Figure 6.3: *System boundaries*

6.1.2 Inventory Analysis

During the inventory analysis phase, data for the system is collected and systematised. The data is ordered into inputs and outputs and classified as well as validated [110][117].

Data Collection

Information about the data collection can be found in Table 6.1.

Table 6.1: *Information about the data collection*

Process	Information and assumptions
Electricity	The electricity used at the plant includes all electricity used as the number is the billed amount of electricity from Agder Energi (distribution company) in 2021. That is also why the warm water process does not include energy to heat the water. The data was collected at Ribe Betong (see Appendix 02).
Aggregates	An attempt was made to obtain data for production from one of Ribe Betong's aggregate suppliers. However, it was unfortunately not possible to obtain enough data to build a representative process in SimaPro. Existing processes were therefore used. It is assumed that these are representative.
Additives	Additives used by Ribe Betong come from Mapei AS. Through e-mail correspondence with K. Fagerheim, a request for data on Mapei's products was sent to their headquarters in Italy. Unfortunately, Mapai could not shear their data and referred to their EPDs. The EPDs were either downloaded from Mapei's website [121] or received by e-mail from K. Fagerheim [122] if not available on the webpage. The EPDs were used in combination with the product data sheets at [121] to choose the best suitable materials in SimaPro to go into the additive processes. Unfortunately, energy use for production was not possible to acquire.
Binders	EPDs and information about Norcem cement and fly ash was found at [123] and [124] and used to compare and choose processes in SimaPro. Due to previous knowledge about Norcem and their position towards sharing background data on their processes, no direct contact was made to obtain data. Transportation distance (1004 km) to the silo in Slemmestad, Norway where Ribe fetches the fly ash, was found at [124]. The fly ash is transported with EURO 6 lorries [125].
Water use	Data on the exact amount of water usage was not possible to obtain for the production line in Kristiansand. Therefore, an estimation was made based on the average from three of Ribe Betong's other production lines. It is assumed this is a representative figure. See Appendix 03 for the calculations.
Transport	Capacity utilisation and any return load have not been taken into account as it was not possible to obtain data on this. EURO6 trucks were assumed if not known from collected data. Google Maps [126] was utilised to find transport distances (see Appendix 04). The distance Ribe Betong transports the finished concrete to customers was found in their general EPD at EPD-Norge [127]. It is assumed it is based on an average of their transportation of fresh concrete. Impacts from the time trucks and pumps are idling is not included in the study as it was not possible to recover this data.
Product	The amount of produced concrete and material use was obtained by e-mail from K. K. Przyworska at Ribe Betong [102].
By-product	The data on Ribe Blokks (Appendix 05) was received by e-mail from Ribe Betong [103]. The by-product production output of Ribe Blokk is not included in the system as they are sold as a side product, and no emissions from the concrete production are allocated there.

Inputs and Outputs

Table 6.2 shows an overview of the inputs and outputs for the analysis. For further information on each process, see Appendix 06.

Table 6.2: *Inputs and outputs of the LCA.* [1)] *100 % allocation to main product, concrete.* [2)] *Cold water for thinning out Mapeair.* [3)] *An output, but due to that it is a self-made waste process it had to be included as input.* [4)] *Transportation of fresh concrete*

Category	Process	Amount	Unit
Product output[1)]	Concrete	287 702 510.00	kg
	Ribe Blokks	8 416 807.00	kg
Materials / Fuels	Ringknut 8-16 K	24 919 663.50	kg
	Birkeland 0/8 G	81 377 836.00	kg
	Omre 0/4 Mix	44 621 208.00	kg
	Omre 2-8 K	1 7942 878.00	kg
	Omre 8-16 K	27 490 994.50	kg
	Omre 16-22 K	15 514 018.30	kg
	LECA 800 4-12	3 495 126.50	kg
	Norcem STD.FA.	43 276 696.00	kg
	Norcem ANL.FA.	4 450 439.77	kg
	Norcem INDUSTRI	1 744 600.09	kg
	Silica fume	1 276 914.61	kg
	Fly ash	488 348.73	kg
	Cold Water	12 899 862.00	kg
	Warm Water	4 078 410 .00	kg
	Cold water[2)]	144 924.87	kg
	Mapeplast P	22 579.58	kg
	Dynamon SX-23	367 267.59	kg
	Dynamon NRG-500	90.04	kg
	Dynamon SX-N	48 049.41	kg
	Mapetard R	33 861.29	kg
	Mapetard SD2000	384.93	kg
	Mappeair 25	7 585.33	kg
	Mapeair 50	42.29	kg
	Mapefast Ultra N	33 663.73	kg
	Mapecure CCI-2000N	87 244.81	kg
	Mapepump Oil	3 362.49	kg
	Stål D4 Dramix	48 153.00	kg
	Stål Sprut 35	1 215.00	kg
	Stål Gulv 50	15 852.00	kg
	PP Fiber	35 253.63	kg
	Plast Gulv 48	288.30	kg
	Plast Sprut 45	116.00	kg
	Wash Water[3)]	24 427 356.50	l
	Transport[4)]	0.004	kgkm
Electricity / heat	Electricity. high voltage	541 701.60	kWh
Waste to treatment	Waste concrete - Sludge	6 850 250.00	kg
	Waste concrete - HCW	8 155 675.00	kg

SimaPro

SimaPro is an LCA software solution that has been used for the LCA calculations in this thesis. It was chosen as it is available for students at the University of Agder. The calculations SimaPro makes are found to have a larger scope than those done by similar LCA tools [128]. The database *Ecoinvent 3 - allocation at point of substitution - unit* in SimaPro was used. It is a database that includes raw materials, products, production processes, transportation and energy, amongst other things. The database is systemised after the attributional approach - each environmental effect is appointed to its related process [129]. It integrates factors that influence both the system or factors that the system can influence [114]. SimaPro separates between market and transformation processes. Market processes consist of output data from multiple or single countries and include a given amount of transport. Therefore, it can be regarded as an average of a variety of transformation processes. Transformation processes are built on information from manufacturing a particular product or service and do not include any transportation. That is why they have been the preferred processes to use in this study. To ensure the most representative analysis of Ribe Betong's process system, all products and processes were built up or adjusted from existing materials and processes in the database to reflect the Norwegian regional conditions Ribe Betong operates under and the location and conditions of their suppliers.

6.1.3 Impact Assessment

The interpretation of the results makes it possible to understand the environmental impacts of the product limited by the system boundaries [110]. In other words, it is the assigning of emissions from the elementary flows of the inventory (for example, resource consumption) into impact categories [130]. ReCiPe2016 was chosen as the characterisation methodology, and midpoint hierarchist (H) approach together with supervisor Reyn O'Born. Figure 6.4 shows how the environmental mechanisms, the midpoint impact categories and the endpoint areas of protection are connected in ReCiPe2016 [131]. Furthermore, their path of damage and, in the end, if it is human health, the ecosystem or resource availability that is damaged. The framework can be described to work as follows: the elementary flows have different outputs (for example CO_2 eq.) that are considered and ordered after effect in the different impact categories at the midpoint. These again have different damage pathways, such as global warming, which has several damage pathways that lead to different kinds of damage. The relationship between midpoint and endpoint characteristics is that the ones at the midpoint have a strong relationship to the flows and little uncertainty. Endpoint has a larger number of uncertainties, but better environmental relevance for the flows [130].

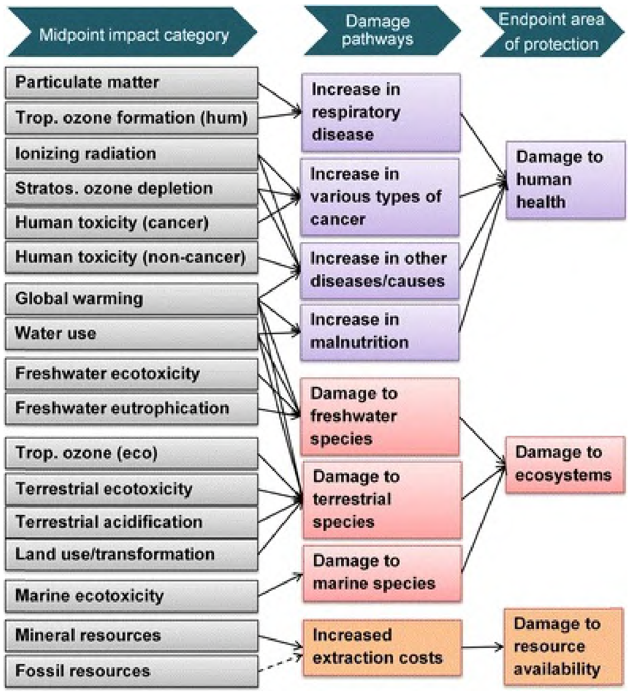


Figure 6.4: *The impact categories and their respected damage pathways and areas of protection [131]*

The midpoint approach is referred to as problem-oriented [120]. Frontera, Malara and Mistretta [120] state that the midpoint approach is often chosen for LCA of concrete because the method employs impacts from the beginning of the chain of cause and effect. It is about reducing uncertainty because the full impact from the late stages is not always known. ReCiPe2016 has midpoint and endpoint (damage oriented) impact categories. There are eighteen impact categories at the midpoint level:

1. Global warming
2. Stratospheric ozone depletion
3. Ionizing radiation
4. Ozone formation, human health
5. Fine particulate matter formation
6. Ozone formation, terrestrial ecosystems
7. Terrestrial acidification
8. Freshwater eutrophication
9. Marine eutrophication
10. Terrestrial ecotoxicity
11. Freshwater ecotoxicity
12. Marine ecotoxicity
13. Human carcinogenic toxicity
14. Human non-carcinogenic toxicit
15. Land use
16. Mineral resource scarcity
17. Fossil resource scarcity
18. Water consumption

Impact categories are used to evaluate how the different impacts of a process that is analysed affect the environment and can be described as environmental issues of concern [132]. Climate change [100 years /kg CO_2 eq.], water consumption [m^3 water consumed], mineral resource scarcity [kg

Cu eq.], and freshwater [kg P eq.] and marine [kg N eq.] eutrophication is mainly looked at in this study.

Global Warming Potential

The impact category Global Warming Potential (GWP) is a widely used comparable measure for GHGs [133]. Its unit is CO_2-equivalents over a given period. The Intergovernmental Panel on Climate Change (IPPC) explains it in this way: "*Global Warming Potentials compare the integrated radiative forcing over a specified period (e.g., 100 years) from a unit mass pulse emission and are a way of comparing the potential climate change associated with emissions of different greenhouse gases*" [134]. In other words, it is the ratio of warming from different kinds of gasses in CO_2-eq. making it possible to compare different climate gasses [135].

Water Consumption

Water consumption is a measure of the total consumption of fresh water for all materials and products in the scenario analysed [132]. Water use includes evaporation for production and discharges into other watersheds or the sea. The water that is consumed is no longer available for any ecosystems or human use [131].

Mineral Resource Scarcity

Mineral resource scarcity can be seen as an average surplus ore potential. It is based on the primary extraction of minerals that lead to a decrease in their associated ore resource concentration. This is then combined with future expectations of extraction of the given mineral [131].

Eutrophication

Eutrophication is when water ecosystems experience an increase in nutrients. This happens naturally by releasing nutrients from earth, rocks and melting of glaciers in water. Water experience additional eutrophication if there is a high amount of nutrients in discharge water from industries, sewage or agriculture [136]. This is known as cultural eutrophication [137] and leads to an overabundance of plankton algae, leading to oxygen loss in the water that can further cause a rise in nutrients (phosphor and nitrogen). Eutrophication in freshwater lakes in Norway increases the pH, disturbing them as the natural habitat for fish and other animals [136].

6.1.4 Scenario Analysis

A scenario analysis was done to look at what happens if making adjustments to the Ribe Betong system. Pesonen et al. [138] defines a scenario LCA as "*a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future*". The scenario analysis aims to analyse other washing techniques compared to Ribe Betong's washing system today.

The same data and system built for the main LCA was adjusted for the scenario analysis. The changes that were made for the different dry washing procedures were:

- Stoning out
  - Uses 2 tonnes of aggregate and 200 litres of water for washing a truck drum [7]. It is assumed that the aggregate can be used again for washing or concrete production. It is further assumed that Ribe Betong would need 10 tonnes of aggregate in inventory for this washing process to be plausible. That way, it is possible to wash five truck drums at once.
  - The SimaPro process *Ringknuten 8-16 K* was used for the aggregate.
  - It is assumed that the amount of CS will not decrease.
- Dry washing
  - 2.1 tonnes of aggregate per wash. The assumption is set to the same amount as in the dry wash test of the empirical work.
  - It is assumed the aggregates can be used up to five times.
  - The SimaPro process *Ringknuten 8-16 K* was used for the aggregate.
  - Wash water consumption is assumed to be reduced by 50 %.
  - The decrease of CS is assumed to be 30 %.
  - It is assumed the aggregate can be re-used for other purposes and is put as by-product output in the same way the concrete blocks were in the main LCA.
- Re-Con Zero washing
  - Waste sludge was decreased by 70 % based on [79].
  - Wash water amount, based on the decrease of sludge amount, was assumed to be 70 %.
  - The amount of RCZ was based on method 1 in the products data sheet [139]. The product data sheet states that the dosage amount is given for consistency class S4 or lower. Concrete that is not included here includes self-compacting concrete and floor concrete [139]. How these types of concrete must be dosed has not been considered in the analysis. This is also since the database does not contain the specific amount of different types of concrete produced but the total amount of concrete.
  - The number of times the RCZ aggregates could be used again was assumed to be 10 times. The assumption is based on findings that the granulated material can be used several times [78], up to two-three weeks when used for daily washing [79].
  - Due to insufficient information available about the content in RCZ, assumptions were made for the scenario analysis on the same terms of the general data collection

[139][121][140]. The content was set to 100 % sodium aluminate.

- It is assumed the RCZ aggregate can be re-used for other purposes and is put as by-product output in the same way the concrete blocks were in the main LCA.

Any additional handling, by hand or machine, of the aggregates is not included in the scenario analysis. An overview of the calculations done can be found in Appendix 07.

6.1.5 Limitations

When utilising information from a case study, it is important to keep in mind that the case may not be representative of all producers of ready mix concrete production [99]. To the extent of the data collected on production, the LCA analysis includes all materials and energy at the concrete plant. The accuracy of the amount of material and electricity used can be seen as high, as the data is used as represented in the respected systems for logging it without any estimations or assumptions. Other data, such as the water used for washing, is based on assumptions and estimations based on available data.

When evaluating washing water, it was calculated that if Ribe Betong uses 1 m^3 per wash, that would mean 94 washes per day in a five-day working week. Even with the use of pumps that use 0.5 m^3 more water per wash, washing of mixers, and other use of water for operation (other than production), the number of washes per day would still be high. It may be that more water is used per wash than is assumed by Ribe Betong or that more water is used than expected for the other things mentioned above.

The processes of the materials and energy are based on processes in SimaPro. Therefore, European and Swiss processes have been chosen wherever possible. It is assumed that these are the most similar to Norwegian conditions. However, in the impact assessment, it was noticed that several of the processes contain global figures. This may create a deviation from actual Norwegian and European conditions.

The emissions comparisons are based on the functional unit, 1 m^3 of produced fresh concrete in 2021, where 1 m^3 equals 2350 kg. From the material list, the use of LECA aggregate indicates the production of lightweight concrete with a density below 2000 kg per m^3. This means that the results will have some deviation from the actual emissions.

EPDs were used when it was not possible to require the needed information in other ways. EPDs are based on the manufacturers' information and released by the manufacturers. This leads to the information readable in the EPD being limited by company secrets, meaning that EPDs are open to bias.

6.2 Dry Washing

The dry washing of the concrete truck drum test was done to investigate a possible alternative to the washing procedure at Ribe Betong today. The method was developed with supervisor Øystein Mortensvik based on previous experience at Ribe Betong. The test was performed at the Ribe Betongs mixing plant in Kristiansand on the 14th of February 2022.

6.2.1 Equipment

- Concrete mixer
- Concrete truck
- Wheelbarrow
- Plastic storage boxes
- Plastic sheet

6.2.2 Materials

Concrete residue

The concrete residue in the concrete truck drum is from a B35M45 concrete. See Table 6.3 for the concrete recipe and information about the concrete batch. The table shows the different materials and their supplier and the amount and the coherent CO_2 eq. where this is known from the suppliers. The *should* column represents the amount of material the specification in the recipe says should be in the produced concrete. The *is* column contains the amount that was weight up for that given batch of concrete produced.

Table 6.3: *Concrete used for laboratory work [141]*

B35M45 D16					
Quality:	B35	Durability class:	M45		
Consistency order/production:	230 mm/230 mm	Mass ratios should/is:	0.410/0.405		
D Max:	18.000	Temperature should/is:	25/18		
Production time:	14.02.2022 07:44				
Material		**Unit**	**Should**	**Is**	**CO_2**
Aggregate	Ringknut 8-16 K	kg	1 670.00	1 678.70	
	Birkeland 0/8 G	kg	1 687.60	1 673.40	
	Omre 0/4 Mix	kg	825.30	818.90	
Cement	Norcem INDUSTRI	kg	1 073.00	1 073.40	802.90
Water	Cold Water	kg	0.00	0.00	
	Warm Water	kg	297.40	297.10	
	Rinsing water	kg	2.00	2.00	
Additives	Dynamon NRG-500	kg	7.60	7.50	14.10
	Mapeair 25 1:19	kg	1.60	1.60	0.90
	Ultra N	kg	11.50	11.50	26.20

Aggregate

Aggregate 8/16 mm Ringknuten was used for the dry wash procedure. The crushing plant Ringknuten Pukkverk AS is approved according to NS-EN 12620 Aggregates for concrete [44]. The LA coefficient of 8/16 mm Ringknuten is 15 [142].

6.2.3 Procedure

Day one

1 Discharge any surplus concrete is discharged into forms for blocks
2 1 tonne 8-16 mm aggregate is added into the drum (see Figure 6.5a)
3 The drum is tumbled for 5 minutes (Figure 6.5b)
4 During the 5 minutes, the aggregates is driven in and out inside the drum so that it does not just lie in the middle of the drum (see Figure 6.5c)
5 To ensure a more representative sample, bout 40 kg of aggregates that come out of the drum is discharged into a wheelbarrow and disposed of
6 About 40 kg of aggregate are discharged into an empty wheelbarrow (see Figure 6.5d)
7 The aggregate is put in plastic storage boxes and transported to the university lab
8 The aggregate is laid out on a plastic sheet to dry (see Figure 6.5e for one day)
9 Another tonne of 8-16 mm aggregates are added into the drum
10 Step 3-8 is repeated to test with 2 tonnes
11 The remaining aggregate is emptied into waste concrete storage (see Figure 6.5f)
12 The inside of the drum was inspected visually

Day two

1 The aggregates on the plastic sheet is put in a plastic storage box and stored dry for further testing

(a) *The aggregate is put in the drum*

(b) *Tumbling for 5min*

(c) *The aggregates are driven in and out*

(d) *Wheelbarrow*

(e) *Let dry*

(f) *Emptying*

Figure 6.5: *Procedure*

6.3 Los Angeles Test

The Los Angeles Abrasion method quantifies the amount of resistance to the crushing of an aggregate. It is done by tumbling the aggregates together with steel balls (see Figure 6.6). It results in an expression for the durability of the aggregate based on the amount of crushed material [143].

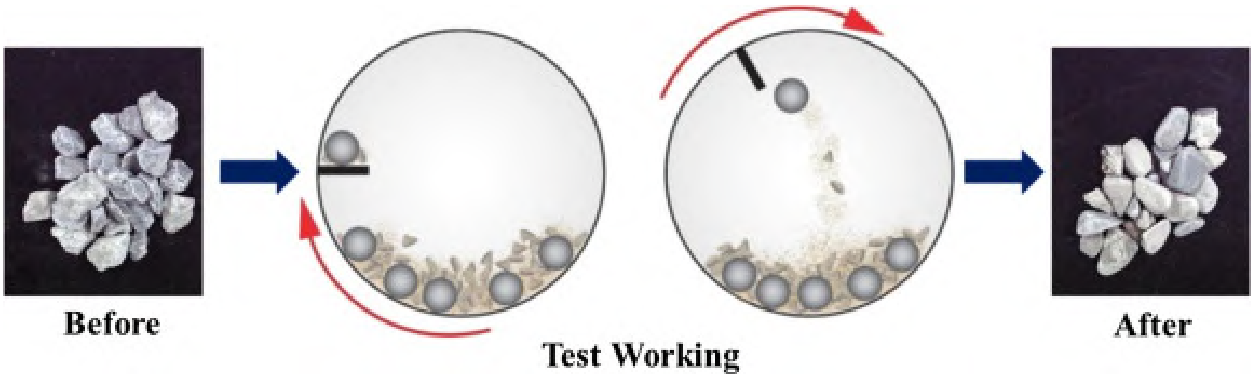
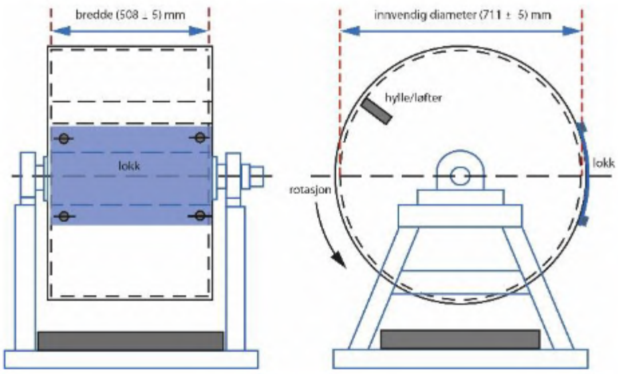


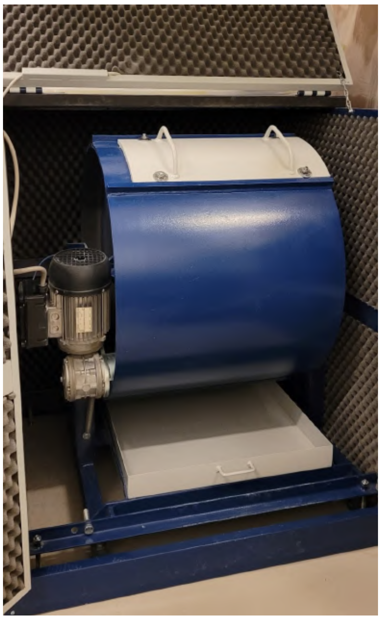
Figure 6.6: *Los Angeles Abrasion test process [144]*

6.3.1 Equipment

- Los Angeles machine with a built-in counter (Figure 6.7a and 6.7b) sett to a total of 500 revolutions at a speed of 31-33 rotations per minute
- Sieves (1.6 mm, 10.0 mm, 12.5 mm and 14.0 mm) (Figure 6.7c)
- Sieve machine (Figure 6.7d)
- Scale (Figure 6.7e)
- 11 steel balls (with 45-49 mm diameter and a weight of 400-445 g each amounting to 4690-4860 g in total)
- Drying cabinet (Figure 6.7f)
- Boxes for storage



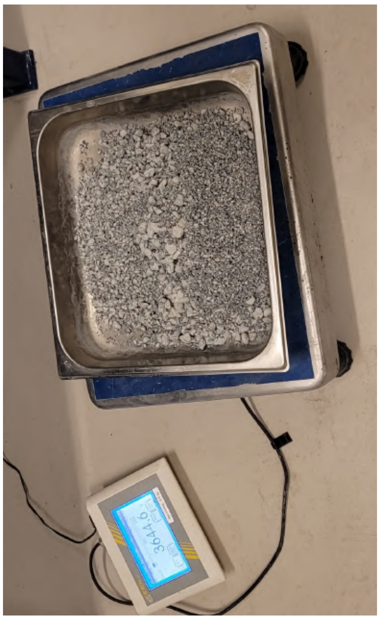
(a) *Sketch of the machine and its required measurements [143]*



(b) *The LA machine at the university lab*

(c) *LA sieves*

(d) *Sieve machine used*



(e) *Scale*

(f) *Drying cabinet*

Figure 6.7: *Equipment for the LA-test*

6.3.2 Procedure

The Los Angeles (LA) procedure was done following the Norwegian Public Roads Administration handbook *R210 Laboratorieundersøkelser 141 Los Angeles-metoden* [143] which is in accordance with NS-EN 1097-2:2020 Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation [145][146]. PhD candidate Solomon Adomako introduced the lab and the LA-test method at UiA.

1. The aggregate was sieved for the test fractions 10.0-12.5 mm and 12.5-14.0 mm.
2. Each test fraction was washed and dried in a drying cabinet at 110°C (R21 allows for ± 5°C [143]). This is to ensure constant mass weight.
3. The aggregate is taken out of the drying cabinet.
4. When it reached room temperature, the test fractions were weight.
5. The total weight of the dry sample was 5000 g (± 5 g [143]).
   5.1 Fracton 10.0-12.5 mm: 3250 g.
   5.2 Fraction 12.4-14.0 mm: 1750 g.
6. The 11 steel balls were placed in the drum of the LA machine.
7. The sample was added.
8. The lid was secured to the machine, and the machine was started.
9. The machine makes 500 revolutions in 15 minutes.
10. When the machine steppes, the lid is opened, and the steel balls are picked out.
11. The sample is tipped out into a tray underneath.
12. The sample was sieved dry (1.6 mm sieve) to eliminate most of the fines before it was washed and dried at 110°C.
13. The sample was taken out of the drying cabinet and let cool down to room temperature.
14. The sample was sieved, and everything larger than 1.6 mm was weighed.

6.3.3 Calculations

R210 [143] gives the equation for calculation of the LA value:

$$LA = \frac{5000 - \mathrm{m}}{50} \tag{6.3.1}$$

m: the weight of material larger than 1.6 mm, given in whole grams

6.4 Literature Study

A literature study is a theoretical approach to data and material from written sources to achieve a comprehensive understanding of a subject [147][148]. It provides insight and an overview of the available knowledge [148] and can be defined as a "*comprehensive study and interpretation of literature that relates to a particular topic*" [149]. It thus entails a systematic search for information, a critical examination, and a comparison of the information found [150] through objective eyes, as well as the search engines used. This is important to ensure reliable and credible information that leads to an overview based on all points of the argument, including literature that contradicts or undermines the project. The literature study for this project was performed to find relevant information and get a broader understanding of the subject.

Strategies learnt from the *Academic Information Seeking course* by the University of Copenhagen and Technical University of Denmark (DTU) [151] taken the autumn of 2020 was utilised in the search process. The course provided an introduction to information seeking and how to evaluate better and document a literature search. Appendix 08 gives the logbook for the literature search. Oria and Google Scholar were the main search engines used. Oria provides literature from the university library at UiA, and other Norwegian academic libraries [152]. Google Scholar [153] has been used to expand the search of academic literature further. When searching for specific topics or to find information outside academic sources, Google [154] was used.

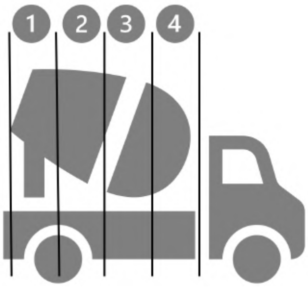
There was no set age limit to searches to ensure that information from earlier times that could be relevant would not be missed. Oria searches were set to "peer-reviewed journals" to make the process more efficient in not needing to check the source if it was peer-reviewed. The primary search language was English, but searches in the Scandinavian languages were also performed, and data and literature received from contributors were used. The search for relevant literature used search terms such as: "recycled washed aggregates from fresh concrete LCA", "gjenvunnet vasket tilslag", "gjenvunnet tilslag fra fersk betong", "concrete reclaimer", and "concrete sludge". In addition to this, Standards Norway's [155] website was used to find relevant standards. A student subscription obtained access. Some of the literature found was citations from other literature. This can be seen as a helpful way of finding more information or data on a specific subject. At the same time, evaluating the referenced sources of the found literature is important. It is, however, important not to concentrate solely on this way of finding more information on a subject, as it can be seen as a pitfall into someone else's search strategies, conclusions and credibility assessments.

7 Results

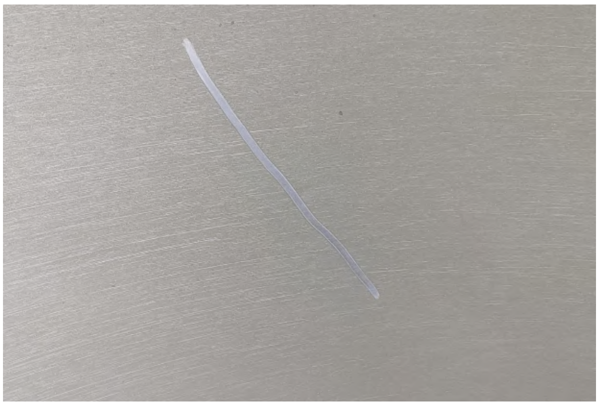
This chapter presents the findings and results of the empirical work, case study and literature review.

7.1 Dry Washing Test

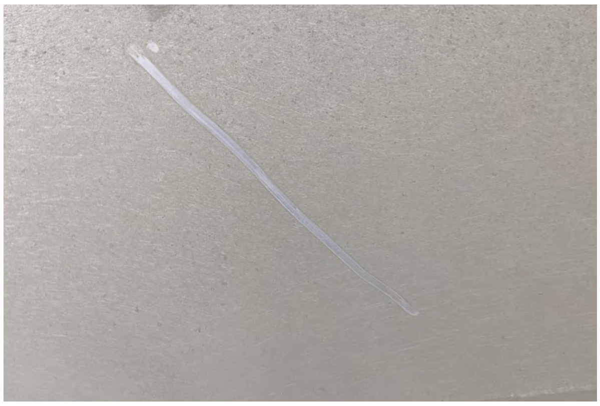
Figure 7.1 shows the results of the dry washing test. The concrete drum is divided into sections, 1 to 4, from the outermost to the innermost part of the drum, Figure 7.1a, and Figures 7.1b to 7.1e show how much concrete residue film was left on the inside of the drum.



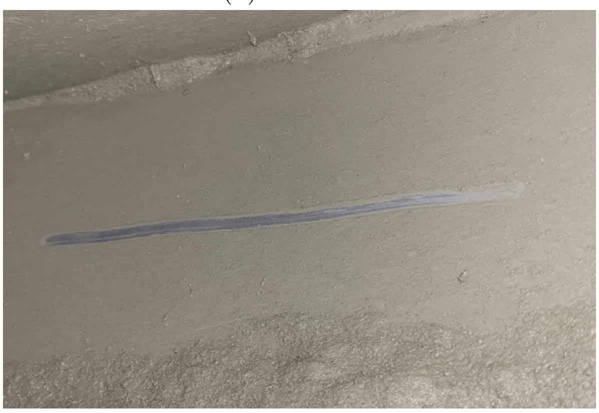
(a) *Overview of sections*



(b) *Section 1*



(c) *Section 2*



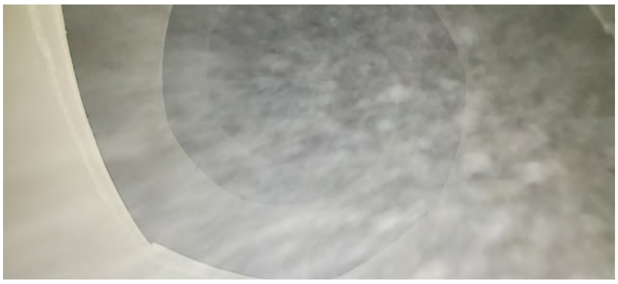
(d) *Section 3*

(e) *Section 4*

Figure 7.1: *Sections with dry washing results*

Figure 7.2a shows the backside of the blades after the dry washing test. The picture also shows hardened concrete residue left on the blades. It was challenging to take photos for documentation inside the drum due to the temperature difference, which made the pictures snowy (see Figure 7.2b). Figure 7.3 shows the aggregate used to wash the drum after discharged from the drum.

(a) *The design of the inside*



(b) *Difficult conditions for photography*

Figure 7.2: Conditions inside the drum

(a) Sample no. 1.1t in wheelbarrow

(b) Sample no. 2.1t in wheelbarrow

Figure 7.3: The dry washing aggregate

7.2 LA-Test

The maximum LA-Values (see Table 7.1) are given in [44]. Table 7.2 gives the LA-values achieved for the tested aggregate samples. The test results show that when adding 1.1 tonnes to the concrete truck drum to clean it, the aggregates achieved LA_{30} and when adding 1 tonne more, the LA category became one level better, LA_{25}.

Table 7.1: *Categories for maximum LA-values. Based on Table 12 in [44]*

Los Angeles coefficient	**Category LA**
≤ 15	LA_{15}
≤ 20	LA_{20}
≤ 25	LA_{25}
≤ 30	LA_{30}
≤ 35	LA_{35}
≤ 40	LA_{40}
≤ 50	LA_{50}
> 50	$LA_{Declared}$
No requirements	LA_{IK}

Table 7.2: *LA-test results for 1.1 tonne and 2.1 tonne (calculations can be seen in Appendix 09)*

Sample no.	**Mass [g]**	**Material < 1.6 mm [g]**	**LA coefficient [-]**	**Category LA [-]**
$1.1t_1$	3461	1164	31	LA_{30}
$1.1t_2$	3645	1309	27	
$2.1t_1$	3916	1030	22	LA_{25}
$2.1t_2$	3939	1020	21	

NS-EN 206 [42] sets a requirement of LA_{50} for concrete up to B25 and LA_{35} for strength classes above that. The Norwegian Public Roads Administration has set additional requirements for B45, and higher to LA_{30} [156]. Adomako, Heimdal and Thorstensen [80] found that agglomerated aggregates from the use of Re Con Zero as a washing agent were within limits for use in new concrete according to NS-EN 206 and for NPRA. Their tests gave LA_{25} for the aggregate.

7.3 Visual Representation of the Aggregate after LA Test

Figure 7.4 shows the particle size distribution of the tested aggregates. It shows that most of the aggregate lies between 8 and 16 mm.

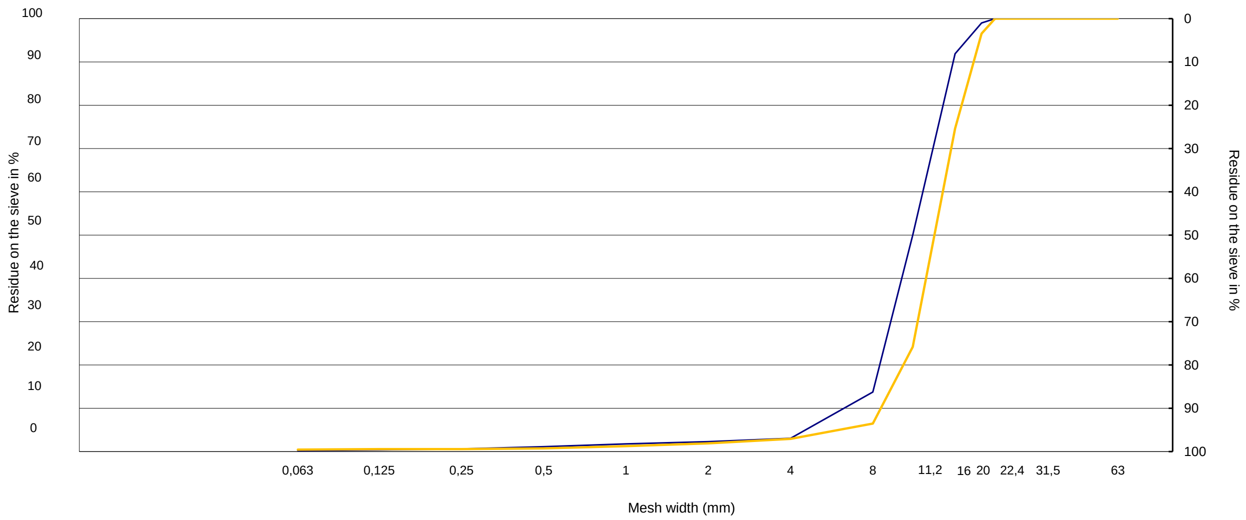
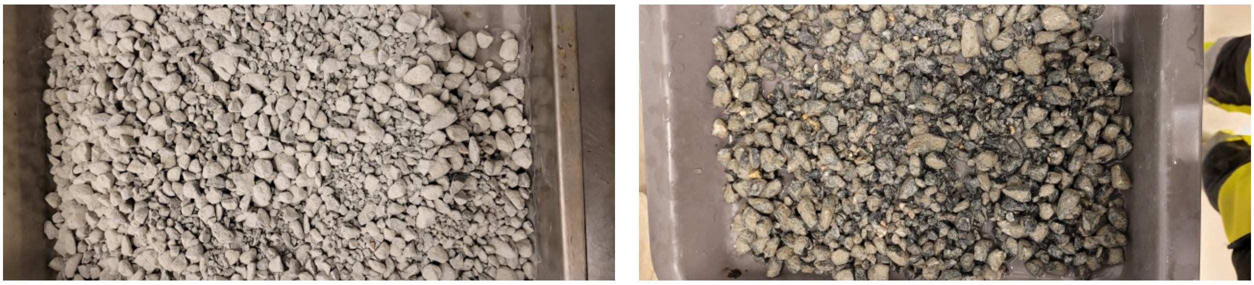


Figure 7.4: *Particle size distribution of aggregate. Yellow: sample no. 1.1t and blue: sample no. 2.1t*

Figure 7.5a shows the aggregates after sieving but before washing. Figure 7.5b shows the wet aggregate after washing.



(a) *Before washing* (b) *After washing*

Figure 7.5: *Aggregates after LA test*

7.4 Regulations, Standards and Guidelines

To ensure unity in practice, concrete manufacturers must follow both standards and legislation.

7.4.1 FABEKO

See Table 7.3 for FABEKOS recommended Normal values that came in 2018. FABEKO also recommended ensuring the pH level not to be too high for the recipient. If the freshwater recipient is sensitive to variations in pH, they recommended the pH of the discharged water to lie between 6.5-9.5 [157].

Table 7.3: *FABEKOS Anbefalte Normalverdier (2018) [157]*

Substance / component	**Normal value in discharge water [mg/l]**
Lead (Pb)	0.1
Cadmium (Cd)	0.02
Copper (Cu)	0.2
Chrome (Cr) total	0.1
Chrome (VI)	should be analyzed
Mercury (Hg)	0.005
Nickel (Ni)	0.5
Zinc (Zn)	0.5
Suspended solids	50

7.4.2 Today's Regulations on Recycling and Treatment of Waste

The Pollution Control Act [158] § 7 states that everyone has an obligation to avoid polluting and that "*no one must have, do or implement anything that may cause a risk of pollution without it being legal under §§ 8 or 9, or permitted by a decision pursuant to § 11*". The regulations on recycling and treatment of waste [159] stipulates that if industrial waste is not to be re-used or recycled, it must be delivered to a licensed landfill. Table 7.4 displays the limits when concrete from the demolition of constructions is to be re-used.

Table 7.4: *§ 14a-4 Requirements for the use of concrete and bricks from demolition projects [159]*

Substance	Concentration limit [mg/kg]
Arsenic (As)	15
Lead (Pb) (inorganic)	60
Cadmium (Cd)	1.5
Mercury (Hg)	1
Copper (Cu)	100
Zinc (Zn)	200
Chromium (III) total	100
Chromium (VI)	8
Nickel (Ni)	75
PCB:	
Σ7PCB	0.01
PAH-forbindelser:	
Σ16 PAH	2
Benzo (a) pyrene	0.1
Aliphatic hydrocarbons:	
Aliphatic C5-C6	7
Aliphatic >C6-C8	7
Aliphatic >C8-C10	10
Aliphatic >C10-C12	50
Aliphatic >C12-C35	100

In the event of an overflow of washing water from concrete production, it is local conditions and the recipient who decides what requirements are set for this type of discharge. It is with the county government that a permit for emissions is obtained.

7.4.3 Coming Regulations

In order to ensure the environmentally friendly operation and that the legislation is complied with, the Norwegian Environment Agency has prepared new regulations that provide equal guidelines for all concrete producers in Norway [160]. The new regulations and possible new requirements (translated by the author) [161]:

§ xx-4. In general about discharges of process wastewater to the recipient

The company must reduce its emissions as far as possible without unreasonable costs.

- *Process wastewater must be recycled as much as possible.*
- *Water consumption must be reduced as much as possible.*
- *Process wastewater shall not cause damage or negative impact on the recipient, and the limit values in § xx-5 and § xx-6 shall be complied with.*
- *Plastic reinforcement fibres must be removed from the process wastewater before discharge.*

§ xx-5 Limit values for heavy metals and suspended solids

Process wastewater shall not exceed the following concentration limits (Table 7.5):

Table 7.5: *Possible concentration limits for process wastewater. Adapted from [161]*

Components	Measurement parameter	Concentration limit (mg/l daily mixed sample)
Lead	Pb	0.1
Cadmium	Cd	0.02
Copper	Cu	0.2
Chromium	Cr-tot	0.1
Chromium (VI)	Cr (VI)	0.03
Mercury	Hg	0.005
Nickel	Nine	0.5
Zinc	Zn	0.5
Suspended solids	SS	30

The limit values must be observed without any dilution before sampling/measurement.

§ xx-6 pH value in emissions

The pH value of the discharge must be adapted to the recipient's tolerable limit but not exceed 9.5. For discharges to vulnerable recipients, the pH value of the discharge water must not exceed 8 [161].

7.4.4 Comparison of Ribe Betong's Wastewater

Table 7.6 shows Ribe Betongs wastewater in comparison to FABEKOS recommendations and the regulations that are assumed to come. The content in the wastewater from Ribe Betong shows the measured values when the wastewater is located in the last chamber of the settling basins.

Table 7.6: *Comparison of Ribe Betong's wastewater, recommendations and coming regulations (CR)*

Substance / Component		Unit	RB	FABEKO	CR
pH		-	11.74	6.5-9.5	9.5
Suspended solids	(SS)	mg/l	171.67	50	30
Arsenic	(As)	mg/l	0.00239		
Cadmium	(Cd)	mg/l	0.00041	0.02	0.02
Cobalt	(Co)	mg/l	0.00546		
Copper	(Cu)	mg/l	0.06578	0.2	0.2
Molybdenum	(Mo)	mg/l	0.39825		
Nickel	(Ni)	mg/l	0.00709	0.5	0.5
Lead	(Pb)	mg/l	0.00850	0.1	0.1
Vanadium	(V)	mg/l	0.01206		
Zinc	(Zn)	mg/l	0.04411	0.5	0.5
Mercury	(Hg)	mg/l	0.00002	0.005	0.005
Chrome	(Cr)	mg/l	0.06481	0.1	0.1
Chromium	VI	mg/l	0.06123		0.03
Chromium	III	mg/l	0.01695		

7.4.5 Comparison of Ribe Betong's Concrete Waste

Table 7.7 shows the average results obtained from Ribe Betong if their sludge. The value for pH of slurry water is in the same range as Wang and Chang [68] found, 10-13.5 amongst 13 studies. It is the presence of cement in the wastewater that raises the pH from ordinary water (pH 7-8) and up [68]. In comparison, the pH level of fresh concrete is between 12.5 and 14 as it is strongly alkaline, and when carbonated, the pH level in concrete is below 9.5.

As the concrete sludge is put in storage basins to dry and harden, the analysis results of Ribe Betong's CS are compared (Table 7.7) to the regulations on the treatment of waste [159] regarding the requirements for the use of concrete from demolition projects.

Table 7.7: *Concrete sludge comparison*

Substance	**Unit**	**RB**	**Limit**
pH	-	11.66	
Total solids (TS)	%	54.41	
Arsenic (As)	mg / kg	7.96	15
Lead (Pb) (inorganic)	mg / kg	19.81	60
Cadmium (Cd)	mg / kg	0.28	1.50
Mercury (Hg)	mg / kg	0.02	1
Copper (Cu)	mg / kg	123.74	100
Zinc (Zn)	mg / kg	115.34	200
Chrome (III) total	mg / kg	-	100
Chrome (VI)	mg / kg	14.58	8
Nickel (Ni)	mg / kg	16.1	75
PCB:			
Σ7PCB	mg / kg	-	0.1
PAH-forbindelser:			
Σ16 PAH	mg / kg	-	2
Benzo (a) pyrene	mg / kg	-	0.1
Aliphatic hydrocarbons:			
Aliphatic C5-C6	mg / kg	<7	7
Aliphatic >C6-C8	mg / kg	<7	7
Aliphatic >C8-C10	mg / kg	<10	10
Aliphatic >C10-C12	mg / kg	<50	50
Aliphatic >C12-C35	mg / kg	379	100

7.5 Life Cycle Assessment

This chapter presents the results of the LCA study.

7.5.1 Overview

Under follows Figure 7.6 which shows all materials categorises and how they are represented in the different impact categories from the production of Ribe Betong's concrete. In Appendix 10 there is a complete overview of the results, and it gives as well an overview of which materials are included in the different material categories in Figure 7.6. The horizontal axis numbers represent the impact categories:

1. Global warming
2. Stratospheric ozone depletion
3. Ionizing radiation
4. Ozone formation, human health
5. Fine particulate matter formation
6. Ozone formation, terrestrial ecosystems
7. Terrestrial acidification
8. Freshwater eutrophication
9. Marine eutrophication
10. Terrestrial ecotoxicity
11. Freshwater ecotoxicity
12. Marine ecotoxicity
13. Human carcinogenic toxicity
14. Human non-carcinogenic toxicity
15. Land use
16. Mineral resource scarcity
17. Fossil resource scarcity
18. Water consumption

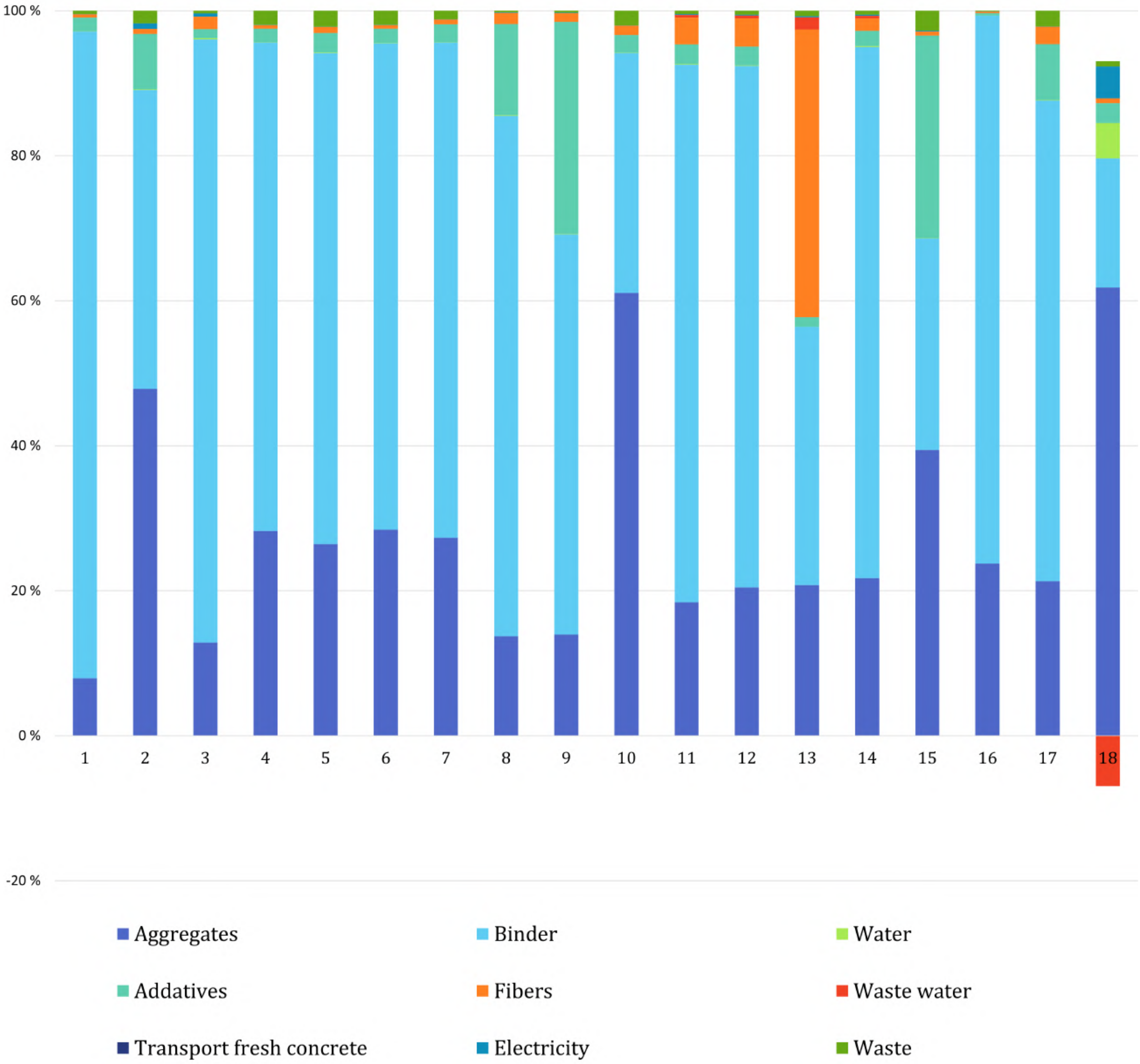


Figure 7.6: *The LCA results divided into materials for all impact categories*

The vertical axis shows the total the different materials contribute. The main contributor in nearly all categories is the binders, followed by the aggregate. Binder stands for the largest amount of the emissions in the impact category GWP while aggregate is about 60 % in both terrestrial ecotoxicity and water consumption. Terrestrial ecotoxicity is pollution that affects land ecosystems and their inhabitants [131].

7.5.2 Global Warming Potential

This analysis shows that Ribe Betong's concrete production in 2021 emitted 240 kg CO_2 per m^3 produced fresh concrete. Figure 7.7 shows how the different components of the process represent a part of the overall GWP. The binder stands for about 89%, the aggregate for 8%, additives 2% and the fibre 0.5% The electricity used, the waste treatment and water treatment account for about the 0.5% remaining. Therefore, the transportation of fresh concrete approximately equals to 0% and the wastewater does not impact GWP.

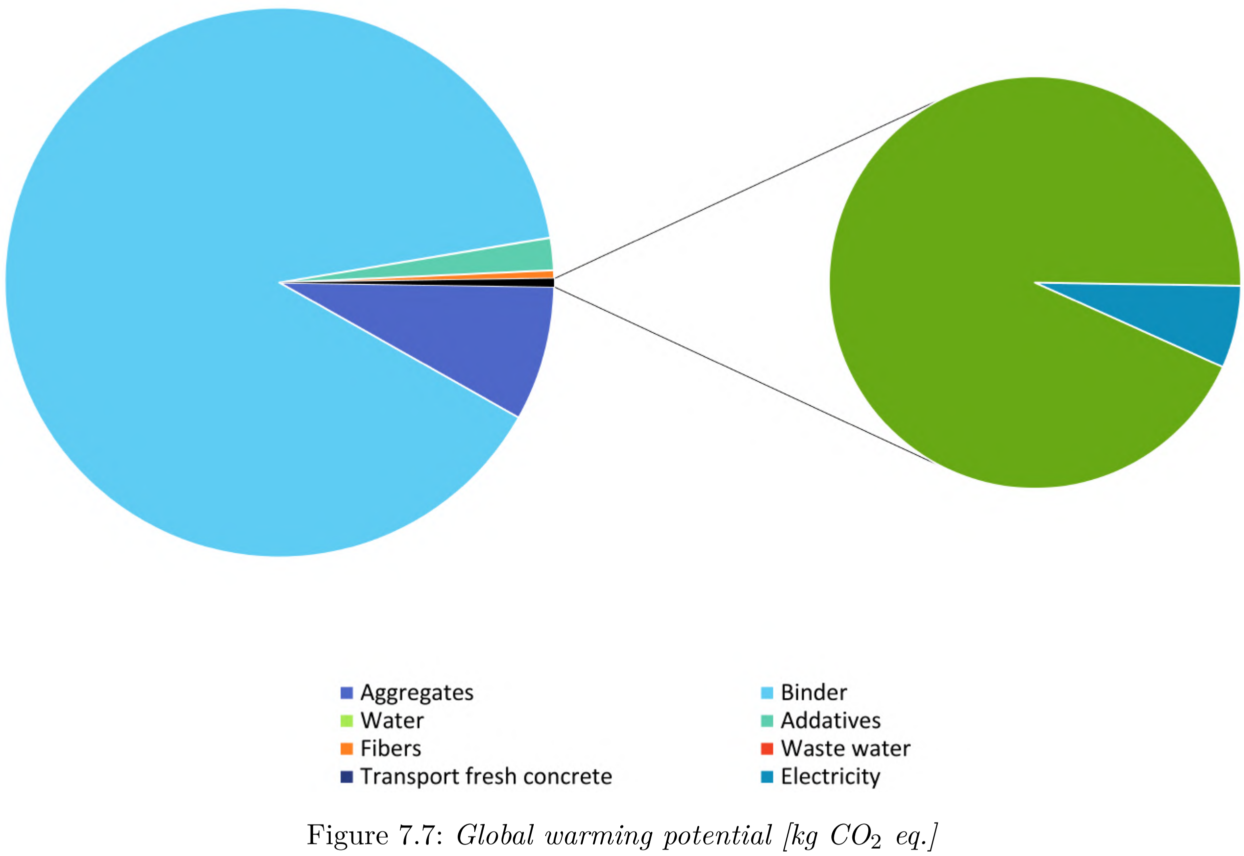


Figure 7.7: *Global warming potential [kg CO_2 eq.]*

Table 7.8 shows how much each input and output contributed to the impact category of global warming potential.

Table 7.8: *Impact Category: Global Warming Potential [kg CO_2]. Colour coding from most in read to least in yellow of total*

Category	Input and output	**Amount**
Total	Concrete produced	240
Aggregate	Ringknut 8-16 K	1.4
	Birkeland 0/8 G	3.4
	Omre 0/4 Mix	2.2
	Omre 2-8 K	0.9
	Omre 8-16 K	2
	Omre 16-22 K	1
	LECA 800 4-12	7.9
Binder	Norcem STD.FA.	176
	Norcem ANL.FA.	25
	Norcem INDUSTRI	12
	Silica fume	0.007
	Fly ash	0.5
Water	Cold Water	0.04
	Warm water	0.01
	Cold water for diluting Mappeair	0.0004
Addatives	Mapeplast P	0.02
	Dynamon SX-23	1.5
	Dynamon NRG-500	0.0004
	Dynamon SX-N	0.2
	Mapetard R	0.03
	Mapetard SD2000	0.001
	Mappeair 25	0.009
	Mapeair 50	4.8E-05
	Mapefast Ultra N	0.1
	Mapecure CCI-2000N	2.7
	Mapepump Oil	0.003
Fiber	Stål D4 Dramix	0.3
	Stål Sprut 35	0.007
	Stål Gulv 50	0.09
	PP Fiber	0.8
	Plast Gulv 48	0.005
	Plast Sprut 45	0.002
Transport	Transport fresh concrete	3E-12
Energy	Electricity	0.07
Waste	Wastewater	0
	Waste - sludge	0.3
	Waste - hardened concrete	0.8

The process flow diagram, Figure 7.8 gives an overview of where the main contributors to the emissions, in kg CO_2 eq. for 1 m^3 concrete produced at Ribe Betong. Most of the impact comes from clinker production. Due to the large amount of standard fly ash cement that is used, this becomes the main contributor. The cut-off is set to 2 % (processes contributing less than 2 % to the emissions are not included in the diagram). The different colour codes for the processes are displayed in the left bottom corner of the Figure.

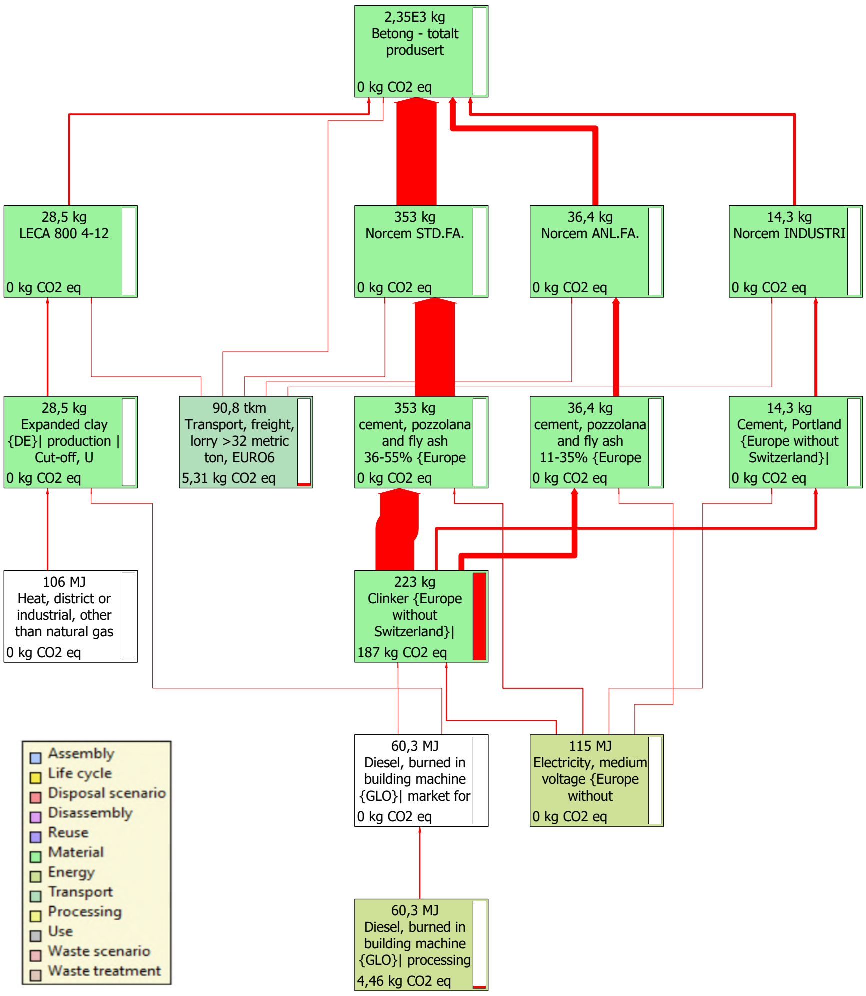


Figure 7.8: *Process flow diagram for GWP [kg CO_2 eq.]*

7.5.3 Mineral Resource Scarcity

The main contributor to mineral resource scarcity (measured in kg Cu eq.) is the use of clay as raw material. Most of it is linked to clinker production, but the expansion of clay for LECA also contributes a substantial amount. The process flow diagrams can be found in Appendix 11. The cut-off is 2 %.

7.5.4 Water Consumption

The analysis shows that most water consumption comes from gravel and sand quarries. Second is the use of lime as raw material for clinker. The third is the water used for electricity production, mainly linked to Ribe Betong's facilities, and some is related to sea transport of steel. Due to wastewater discharge back to nature, this component is regarded as a minus concerning water consummation. The process flow diagrams can be found in Appendix 11. The cut-off is 2 %.

7.5.5 Eutrophication

The cut-off was set to 2 %. The process flow diagrams can be found in Appendix 12.

Fresh Water Eutrophication [kg P eq.]

The analysis shows that the primary source of eutrophication stress comes from the cement and is generated in the clinker production process. It is caused by the processes energy input, from coal mine operations and electricity production (lignite mine operations). The reason these operations cause this stress is the treatment of waste and the disposal in landfills and how this affects its surrounding environment. Other causes are the production of expanded clay for LECA, Mappecure, an additive that contains organic oil (wastewater from the oil refinery), sea transport and production of electric energy for steel fibre and energy to run Ribe Betong's concrete plant (the fossil fuel processes in the Norwegian high energy mix).

Marine Eutrophication [kg N eq.]

As for above, the primary source of eutrophication stress comes from cement production, some from organic oil components in Mapecure, a bit from LECA and some from the steel fibre and electricity use at Ribe Betong. In addition, some of the impacts come from gravel and sand production originating from steel production. It is assumed that the steel in these processes is used to produce equipment for crushing, sieving or similar.

7.5.6 Scenario Analysis

Overview

Table 7.9 shows the total impact on all the different impact categories from the different scenarios of washing procedures. The colour coding helps to see the difference in the impact of the different procedures compared to each other. For further detail, see Appendix 13. The results show that the RCZ process has the lowest impact, while dry washing shows the highest. Regarding water consumption, the process today at Ribe Betong returns more water to the natural system. At the same time, this process uses the most water (see Chapter 6.1.4 for the changes made for the scenarios).

Table 7.9: *Comparison of Ribe Betong's today versus other washing procedures. RB: Ribe Betong today, SO: stoning out, DW: dry washing and RCZ: Re-Con Zero procedure*

Impact category	**RB**	**SO**	**DW**	**RCZ**	**Unit**
Global warming	239.8	239.8	240.0	239.2	kg CO2 eq
Stratospheric ozone depletion	0.0000399	0.0000399	0.0000414	0.0000396	kg CFC11 eq
Ionizing radiation	8.25	8.25	8.26	8.23	kBq Co-60 eq
Ozone formation, Human health	0.51	0.51	0.52	0.50	kg NOx eq
Fine particulate matter formation	0.164	0.164	0.165	0.162	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	0.514	0.514	0.525	0.508	kg NOx eq
Terrestrial acidification	0.460	0.460	0.468	0.458	kg SO_2 eq
Freshwater eutrophication	0.03193	0.03193	0.03197	0.03190	kg P eq
Marine eutrophication	0.002810	0.002810	0.002821	0.002807	kg N eq
Terrestrial ecotoxicity	308.2	308.2	310.8	304.2	kg 1.4-DCB
Freshwater ecotoxicity	2.759	2.751	2.766	2.745	kg 1.4-DCB
Marine ecotoxicity	3.75	3.74	3.76	3.73	kg 1.4-DCB
Human carcinogenic toxicity	11.3	11.2	11.3	11.1	kg 1.4-DCB
Human non-carcinogenic toxicity	62.3	62.1	62.4	62.0	kg 1.4-DCB
Land use	4.24	4.24	4.25	4.19	m^2a crop eq
Mineral resource scarcity	1.570	1.570	1.571	1.569	kg Cu eq
Fossil resource scarcity	25.88	25.88	25.90	25.60	kg oil eq
Water consumption	2.47	2.63	2.58	2.60	m^3

Changes were made to the amount of wash water and waste concrete for the scenario analysis. The stoning out and dry wash procedures have the addition of aggregate, and the Re-Con Zero procedure has the addition of Re-Con Zero powder.

Global Warming Potential

Table 7.10 shows how these changes affect the impact on GWP.

Table 7.10: *Differences in GWP based on the different scenarios and today's procedure.* 1) *No additions,* 2) *No impact in this category*

	RB	**SO**	**DW**	**RCZ**	**Unit**
Wash water 2)	0	0	0	0	kg CO_2 eq.
Addition	0 1)	0.0006	0.5813	0.0002	kg CO_2 eq.
WC	1.06	1.06	0.75	0.49	kg CO_2 eq.

Water Consumption

Table 7.11 shows how the changes affect the impact on water consumption.

Table 7.11: *Differences in water consumption based on the different scenarios and today's procedure.* [1)] *No additions. WC: Waste concrete. both hardened and sludge*

	RB	SO	DW	RCZ	Unit
Wash water	-0.20	-0.04	-0.10	-0.06	m^3
Addition	0[1)]	6E-06	7E-03	4E-07	m^3
WC	0.02	0.02	0.02	0.01	m^3

Mineral Resource Scarcity

Table 7.12 shows how the changes affect the impact on mineral resource scarcity.

Table 7.12: *Differences in mineral resource scarcity.* [1)] *No additions,* [2)] *No impact in this category*

	RB	SO	DW	RCZ	Unit
Wash water[2)]	0	0	0	0	kg Cu eq
Addition	0[1)]	1.6E-06	1.7E-03	3.3E-07	kg Cu eq
WC	0.0017	0.0017	0.0012	0.0008	kg Cu eq

Fresh Water Eutrophication

Table 7.13 shows how the changes affect the impact on freshwater eutrophication.

Table 7.13: *Differences in fresh water eutrophication.* [1)] *No additions,* [2)] *No impact in this category*

	RB	SO	DW	RCZ	Unit
Wash water[2)]	0	0	0	0	kg P eq
Addition	0[1)]	5E-08	6E-05	1E-08	kg P eq
WC	7E-05	7E-05	5E-05	4E-05	kg P eq

Marine Eutrophication

Table 7.14 shows how the changes affect the impact on marine eutrophication.

Table 7.14: *Differences in marine eutrophication.* [1)] *No additions,* [2)] *No impact in this category*

	RB	SO	DW	RCZ	Unit
Wash water[2)]	0	0	0	0	kg N eq
Addition	0[1)]	1.21E-08	1.24E-05	1.33E-09	kg N eq
WC	7E-06	7E-06	5E-06	3E-06	kg N eq

8 | Discussion

8.1 Dry Washing Test

It is not easy to see in the pictures from the dry wash test (Figure 7.1), but the concrete residue film may be thinner in the innermost section and becomes thicker for each section outwards. This result corresponds with how the inside of the drum felt when pulling a finger over its inside. Adding another tonne of aggregates may have given less residue inside the drum as there would be more surface area for the concrete residue to stick on.

The residue in the drum was assessed to tick to be able to let it stand overnight and use the drum again in the morning without washing it with water first. It is, however, evident from the concrete residue that stuck on the aggregates that there would be fewer solids in the washing water after the dry washing procedure, and this would lead to faster sedimentation in the basins as well as lower values in the wash water because there is less matter in it. Further, this would result in the period of the cycle of wash water decreasing, resulting in Ribe Betong being able to use more of its wash water instead of including new water into their system when the solids in the wash water has not sedimented so the wash water can to be used again. The lower values would also be positive for events of overflow.

Adding another tonne of aggregates to the drum instead of doing it as two experiments, one with 1 tonne of aggregates and another one with 2 tonnes, may have given different results, but they would likely be similar. The design of the experiment was chosen so that not too much virgin aggregate would have to be disposed of for the experiment. Today's concrete standards do not include "washing aid aggregate". The closes to any of the defined aggregates would be reclaimed washed aggregate, "*aggregates gained by washing fresh concrete*" [42]. However, this definition does set limitations to the amount of it that can be re-used in concrete. If not, extensive testing and control need to be performed for classification following NS-EN 12620 Aggregates for concrete [44].

8.2 LA-Test

The Los Angeles test provided evidence that in regards to crushing, aggregate that has been used for dry washing can be utilised in concrete. The 1.1 tonne samples had more concrete residue that wore off from the tumbling of the LA machine, and ended up as the material smaller than 1.6 mm than the 2.1 tonne sample. Hence, the better LA category for the 2.1 tonne sample. This can also be seen when comparing Figures 7.3a and 7.3b to Figure 7.5.

The dry washing test got similar results to Adomako, Heimdal and Thorstensen [80] test of aggregate from dry washing using a two-component admixture. The difference between these two types of washing aggregate is that the sample tested in this thesis was made using virgin aggregate for washing, while the granulated aggregate is made out of RCW. So the latter will contain more concrete residue around the aggregate (that was a part of the original concrete). Granulated aggregate is sold as a circular economic and sustainable alternative to landfills [81]. Avoiding landfills is essential, and the best solution would be no RCW. This would require higher accuracy in calculations and a smaller safety margin for orders. Always having the possibility to re-use the produced concrete for equivalent or suitable projects keeps the material within its circular economic cycle longer. It is, however, not likely to be achieved due to the extra need for logistics and planning. It would also affect the continuity in the work of concrete manufacturers.

The declared LA value for the aggregate utilised for the dry washing was LA_{15} [142]. Since the drum had much residue still in after the dry washing test, the LA value from the 2.1 tonne test is likely to be the most comparable of the two test values if this washing procedure was to be utilised. If more aggregate was used, it could improve the LA category. In other words, the use as a dry washing agent has reduced the aggregate's residence to crushing from the best LA category, LA_{15}, by two categories, to LA_{25}.

8.3 Life Cycle Assessment

The results from the LCA showed that in nearly all impact categories, the binder is the main contributor to emissions, followed by the aggregate. This is because cement production requires a lot of raw material extraction and is an energy demanding process. This was further viewed closer when looking at the different process flows (Chapter 7.5.2 to 7.5.5). Further, the results show that aggregates also account for some of the emissions from different impact categories. As concrete consists of approx. 65 % aggregate, which requires material extraction from nature. This results in high impact.

8.3.1 Global Warming Potential

There is a strong focus on CO^2 emissions when discussing sustainability and the climate impacts society has on the globe. This also applies when it comes to emissions concerning concrete. Not surprising, when 9 % of the world's CO^2 emissions come from concrete [1]. When comparing the different material inputs in Ribe Betong's concrete production, cement stands for 89 % of the GWP. When compared to the world average of 83 % [1], the LCA results of this thesis are a bit higher.

The results showed that the GWP related to 1 m^3 of concrete is 240 kg CO^2 eq. According to the Norwegian Concrete Associations industry reference from 2019, this is the same as a B20 strength class concrete [98]. Furthermore, from the case study, it is known that 40 % of the volume of produced concrete at Ribe Betong had a strength class of B30 [104], which has GHG emissions of 280 kg CO^2 [98].

When assessing the GWP of concrete, it is evident that a reduction in emissions from cement that will lead to lower total emissions from concrete. The process flow diagram, Figure 7.8, shows that in addition to the clinker production, the choice of energy sources will have some impact on the GWP from cement. Much work in this field is already done [1][2]. It is conceivable that concrete producers will have to work extra hard to show their sustainable sides as they may seem small due to the sizeable CO^2 footprint that originates from cement production. Therefore, it may be essential to carry out and shed light on the measures taken locally by the producer that contribute to holistic, sustainable development for society. Sustainability is more complex than just CO^2 emissions, and it is important to also look at other impact categories.

8.3.2 Mineral Resource Scarcity

The LCA results showed that the raw material extraction for cement production stands for most of the resource depletion for concrete production. Concrete producers can utilise SCMs in their production to compensate for some of this. As well as put pressure on their cement suppliers to ensure that effort is put in place to ensure the best utilisation of the raw material for cement. New materials and technologies can also help to minimise the need for cement. The same goes for the use of natural sand and rock as aggregate. When 50 % of the produced aggregate from granite ends up as waste [46], it is crucial to implement circular thinking to ensure its re-use and lower the number of natural resources that need to be extracted. Target 12.5 of the UNs sustainability goals is by 2030 to *substantially reduce waste generation through prevention, reduction, recycling and re-use* [28]. If this is to be achieved, concrete producers can play a role in the amount of re-use of waste from all processes leading up to concrete material production and concrete waste of cause.

8.3.3 Water Consumption

The analysis shows that the impact category of water consumption is also affected by the extraction of raw materials for the materials in concrete. Therefore, a concrete producer's sense of social responsibility and determination towards sustainable production is vital for their choice of material suppliers. Furthermore, if incorporating SDGs in day-to-day operations, concrete suppliers can help in the work to achieve Target 12.2, *by 2030, achieve the sustainable management and efficient use of natural resources* [28].

8.3.4 Eutrophication

The recipient of discharge water must have sufficient buffer capacity to withstand what is released. The results of eutrophication can also be seen as a problem field where the concrete producers need to pressure their suppliers to ensure the sustainable consumption and production patterns of the materials for concrete.

8.3.5 Scenario Analysis

The scenario analysis shows little impact difference between the Ribe Betong system today and the three scenarios. The water usage at Ribe Betong includes all water use on the plant, not only for washing. In the scenario analyses, it has been considered to be only washing water. It is, therefore, likely that the scenarios analysed would, in real life, have a bit higher levels on the impact categories affected by the higher water usage than has been accounted for by the analysis.

Stoning Out

Compared to today's practice at Ribe Betong, 80 % of the wash water usage was reduced. The amount of waste was kept the same because the amount of concrete residue will be the same even though this washing method is used. It will, however, be less water usage. This might lead to a shorter period of sludge dewatering because the sludge contains less water than the sludge of today's practice. The scenario was based on the premise that the aggregate used for stoning out can be utilised in new products and would not result in waste. If this was not the case, the analysis would likely give different results.

Reducing water use in the concrete industry can be a large part of increasing its sustainability profile. While 2.2 billion people lack safe drinking water [36], 1.7 % of freshwater that could have gone to satisfy the shortage is used for concrete production [41]. Therefore, when concrete is used in such large amounts, it is crucial to ensure that its water comes from sustainable withdrawals and is utilised as efficiently as possible.

Dry Washing

The scenario analysis showed that dry washing had the highest impact, even though not much. The scenario was based on the premise that the aggregate used for dry washing can be re-used in new products and would not result in waste. If this was not the case, the analysis would likely give different results. If the dry washing procedure should aid in decreasing the amount of CS accumulated, a large amount of aggregate would need to be used. There was not time to investigate if the aggregates in practise could be used several times as with the RCZ method. If this is possible, the dry wash procedure would not require such a large amount of aggregate.

Re-Con Zero procedure

The RCZ procedure resulted in lower emissions than Ribe Betongs practise today. The scenario was based on the premise that the aggregate created by the procedure can be re-used in new concrete production and would not result in waste. If this was not the case, the analysis would likely give different results. Based on the results available, it is difficult to assess if the use of RCW for granulated aggregates is better than using the RCW for a new use such as concrete blocks. A comparative LCA with a more comprehensive database would need to be performed. However, based on the definitions in the standard for reclaimed and recycled aggregate, RCZ aggregate does not automatically comply with the continued use in concrete. Concrete blocks for non-constructive purposes are a by-product that is possible to sell. They can be seen as one of the concrete industries shifting towards a circular economy, utilising excess material for new use. However, it is in one of the broader cycles of the butterfly diagram indicating that other solutions should be made use of if they can lead to keeping the RCW as material for a longer time possible in the cycle. The GHG emissions from material use have increased since the 2000s [28] and we are depleting or non-renewable resources [1]. This supports the need for production processes to use their by-products instead of natural raw materials unless solutions can be found that create interaction and chained use of the by-products with the best option for utilisation. This requires system thinking and a comprehensive view.

8.4 Regulations, Standards and Guidelines

When comparing the values in the analysis of wastewater at Ribe Betong to FABEKOS normal levels, all levels are under what the industry association consider typical values (see Table 7.6). It is assumed these numbers are based on feedback from their member companies. Even though the values are from 2018, it is not likely to believe the wastewater from a concrete plant has changed much since then, as the production of concrete and its materials has not changed much ether. However, in regards to corporate social responsibility, the expectations from society in terms of what people in the society are concerned about and changes made to legislation, companies and industries must adjust according to the social expectations to maintain their recognition in society [29].

The suspended solid level is the only level over the normal levels. It may be that this is as much as three times as high because the sample at Ribe Betong is taken in their last sedimentation basin and not in the last basin before overflow. This is where the actual discharge water will be located. Samples taken in sedimentation basins may have variations if the basins are congested or freshwater has just been introduced with suspended matter that has not been allowed to stand long enough to settle.

When comparing the content in Ribe Betongs wastewater (Table 7.6) with the requirements in the new concrete regulations, Ribe Betong's average values are mainly within the new requirements. However, the suspended solids are way over what will be permitted. If this wastewater was to be discharged into a freshwater ecosystem, it would *significantly reduced fishing* [83], and in a sea environment, it could sludge the bottom. The pH level is alkaline at such a level that *all fish species die in a short time* [86]. The alkaline pH gives chromium III conditions to shift to Chromium VI [88] which might lead to a higher concentration of chromium VI that is already over the limit that will be allowed for wastewater if the regulations are implemented. As the chromium VI in the wastewater comes from the cement, it could be that in addition to implementing new regulations on the concrete producers, the contents of soluble chromium VI must be lowered in the cement by the cement manufacturers. This can be seen as a sustainable way of thinking, as it would ensure better cradle-to-cradle prerequisites for cement. In addition, ensuring efficient enough sedimentation will ensure that solids containing chromium will be taken out of the wash water. Because the values are average values for all the content, it is believed that some sample tests may be over the allowed limit, and some are below.

The comparison of Ribe Betong's sludge to the limits for recycled concrete from demolition projects (Table 7.7) shows that there are too high levels of copper, and chromium VI and aliphatic hydrocarbons. The copper content is assumed to come from the aggregates. The aliphatic hydrocarbons are assumed from formwork oil, incorrect use of diesel as lubrication in pump hoses, accidents with hydraulic hoses and others. It is believed that the aliphatic hydrocarbons should be possible to keep within limits if proper use and handling of the substances listed above is done. However, the contents of chromium VI might be higher in the sludge (the state of which the sample for analysis is taken at Ribe Betong) than it will be when the sludge is hardened and dewatered (naturally by run-off and evaporation under controlled conditions (settling basins to control run-off)). This might depend on whether there is a lot of chromium VI that is soluble in the water contents or in the solid matters that will stay in the slurry when it hardens.

Target 6.3 of the SDGs can be used as a purpose for the work of controlling and ensuring that wastewater from concrete production does not negatively affect the environment. The target aims by 2030 to *improve water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe re-use globally* [39]. Incorporating the targets and taking measurable measures to achieve them will be a way to quantify and thus show its sustainability profile externally. Furthermore, by implementing action plans such as the European Green Deal and sharpened legislation, it is evident that change to environmentally friendly and sustainable solutions is crucial for the survival of ready mix concrete companies.

9 Conclusion

This master's thesis has studied ready-mix concrete producers concerning sustainability, and the research question has been as follows:

How can the concrete industry improve its sustainability profile with the re-use of surplus fresh concrete and its by-products?

The focus on sustainable production is increasing amongst the companies in the construction industry. Measures have been taken towards improving their sustainability profile, such as the re-use of surplus fresh concrete in the production of non-construction purposes blocks, re-use of wash water, knowledge about the content of their discharge water, and the increase in environmentally certified companies.

To improve the sustainability profile of concrete producers, taking the whole life cycle of concrete into account and being in control of the system and its contents is vital. This ensures a sustainable future for further generations. A beneficial option is to incorporate a circular economy with no waste, where most of the concrete producer's waste materials can be circled back for new use at their own facilities. To achieve this, combinations of solutions will probably have to be used. The drive for innovation and searching for better solutions that lead to technological improvements will distinguish the ones with a leading sustainability profile from the others.

The subquestions of the research question have been:

How can dry washing of concrete truck drums influence the possible use of reclaimed aggregates?

> The dry washing aggregate was not found to fit the concrete standards definition of reclaimed aggregates. The LA-test did show that in regards to crushing, the dry washing procedure did not affect the aggregate in such a way that it was outside the limits for use in concrete.

What are the environmental effects of dry washing?

> The empirical work showed that a large amount of aggregate would be needed for dry washing. According to the scenario analysis, this would negatively affect the environmental impact coming from concrete production. One would also have a lot of washing aggregate, which the production of new concrete will not be able to utilise due to the standard today. If dry washing is to be considered an option, ensuring that there is a use for the amount of washing aggregate is crucial to ensure the sustainability of the procedure.

How does the wastewater from the ready-mix concrete plant impact the environment if it is discharged?

The content of the wastewater makes it necessary to handle the water before it is discharged. Another option is to ensure a circular and closed system that does not allow for pollution of its surrounding environment.

How do regulations and standards affect the use of surplus fresh concrete and concrete by-products in the construction industry?

The regulations and standards open up for minor use of surplus fresh concrete and concrete by-products to ensure good re-use and a sustainable future. Further incorporation of sustainability and circular economy thinking into the entire value chain, including the framework for manufacturers, can help open up a better sustainability profile for concrete producers and the construction industry as a whole.

10 | Recommendations

The LCA of concrete production contains many components for input and output. As a result, there is a large amount of data to be collected and processed. Data collection and processing is a time-consuming process in itself. It involves much waiting and hopes to receive data in the amount and accuracy needed to achieve the desired quality of the analysis. A sufficient amount of data can only be achieved when suppliers and manufacturers willingly share information regarding their processes.

Furthermore, it would be desirable to have more accuracy for Norwegian conditions in the SimaPro processes that already exist when it is necessary to use these. For this, data must be more accessible to researchers. The industry must desire to release more information, and researchers, users and manufacturers of SimaPro and its databases must further process and share this information.

With more time available, changes regarding the chosen impact categories for the impact assessment could give a different result. Freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity would firstly be looked at.

A more thorough impact assessment would also be possible. To further ensure the quality of the assumptions and estimates made based on limited information in EPDs and data sheets, individual analysis of the products in SimaPro is recommended.

The dry washing test found that there would be a less amount of solids in the drum, which in turn would lead to less amount of regulated substances in the washing water. However, further research should test the washing water from a dry-washing test to be sure of this.

Other tests on the dry wash aggregate, such as flakiness index, water absorption and particle density, and testing it as aggregate for concrete, could further indicate its usability. Solutions for recycling and reuse outside the concrete plant are seen as another possible approach for further studies.

To ensure that concrete producers comply with goals of being more sustainable and operating within regulations, knowledge of the content and pollution risk of the waste they have must be in place. In addition, looking into solutions best suited for the given problem areas at each concrete plant will be beneficial.

Bibliography

[1] D. Coffetti, E. Crotti, G. Gazzaniga, M. Carrara, T. Pastore, and L. Coppola, "Pathways towards sustainable concrete," *Cement and Concrete Research*, vol. 154, p. 106718, 2022.

[2] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry," *Cement and Concrete Research*, vol. 114, pp. 2–26, 2018. Online]. Available: https://www.sciencedirect.com/science/article/pii/S0008884618301480.

[3] P. J. Monteiro, S. A. Miller, and A. Horvath, "Towards sustainable concrete," *Nature materials*, vol. 16, no. 7, pp. 698–699, 2017.

[4] V. W. Tam and C. Tam, "Economic comparison of recycling over-ordered fresh concrete: A case study approach," *Resources, conservation and recycling*, vol. 52, no. 2, pp. 208–218, 2007.

[5] Statistics Norway, *Avfall fra byggeaktivitet*, 2021. Available: https://www.ssb.no/natur-og-miljo/avfall/statistikk/avfall-fra-byggeaktivitet. Accessed: 21. May 2022.

[6] D. Xuan, C. S. Poon, and W. Zheng, "Management and sustainable utilization of processing wastes from ready-mixed concrete plants in construction: A review," *Resources, Conservation and Recycling*, vol. 136, pp. 238–247, 2018.

[7] B. Sealey, P. Phillips, and G. Hill, "Waste management issues for the uk ready-mixed concrete industry," *Resources, Conservation and Recycling*, vol. 32, no. 3, pp. 321–331, 2001.

[8] J. V. Martins, D. C. S. Garcia, M. T. P. Aguilar, and W. J. dos Santos, "Influence of replacing portland cement with three different concrete sludge wastes," *Construction & building materials*, vol. 303, p. 124519, 2021.

[9] World Economic Forum, "The Global Risks Report 2022," Geneva, Switzerland, 17th ed., 2022 Accessed: 26 April 2022. [Online]. Available: https://www.regjeringen.no/no/tema/klima-og-miljo/klima/innsiktsartikler-klima/klimatilpasning/id2344803/.

[10] Klima- og miljødepartementet, *Slik kan vi tilpasse oss klimaendringene*, 2021. Available: https://www.regjeringen.no/no/tema/klima-og-miljo/klima/innsiktsartikler-klima/klimatilpasning/id2344803/. Accessed: 26 April 2022.

[11] L. Bevere and Dr. A. Weigel, "Natural catastrophes in 2020: secondary perils in the spotlight, but don't forget primary-peril risks," Swiss Re Institute, Zurich, Switzerland, No 1, 2021, Zurich, Switzerland.

[12] L. Bevere and Dr. F. Remond, "Natural catastrophes in 2021: the floodgates are open," Swiss Re Institute, Zurich, Switzerland, No 1, 2022, Zurich, Switzerland.

[13] Statistics Norway, *Hva er egentlig BNP?*, 2021. Available: https://www.ssb.no/nasjonalregnskap-og-konjunkturer/nasjonalregnskap/statistikk/nasjonalregnskap/artikler/hva-er-egentlig-bnp. Accessed: 10 May 2022.

[14] T. Frederikse, M. K. Buchanan, E. Lambert, R. E. Kopp, M. Oppenheimer, D. Rasmussen, and R. S. W. v. d. Wal, "Antarctic ice sheet and emission scenario controls on 21st-century extreme sea-level changes," *Nature communications*, vol. 11, no. 1, pp. 390–390, 2020.

[15] D. Le Bars, S. Drijfhout, and H. de Vries, "A high-end sea level rise probabilistic projection including rapid antarctic ice sheet mass loss," *Environmental research letters*, vol. 12, no. 4, p. 44013, 2016.

[16] T. Slater, I. R. Lawrence, I. N. Otosaka, A. Shepherd, N. Gourmelen, L. Jakob, P. Tepes, L. Gilbert, and P. Nienow, "Review article: Earth's ice imbalance," *The cryosphere*, vol. 15, no. 1, pp. 233–246, 2021.

[17] S. A. Kulp and B. H. Strauss, "New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding," *Nature communications*, vol. 10, no. 1, pp. 4844–12, 2019.

[18] H. Yang, G. Lohmann, W. Wei, M. Dima, M. Ionita, and J. Liu, "Intensification and poleward shift of subtropical western boundary currents in a warming climate," *Journal of geophysical research. Oceans*, vol. 121, no. 7, pp. 4928–4945, 2016.

[19] B. Evengård and T. Thierfelder, "Clinf: Climate-change effects on the epidemiology of infectious diseases, and the associated impacts on northern societies," in *Nordic Perspectives on the Responsible Development of the Arctic: Pathways to Action*, Springer Polar Sciences, pp. 49–70, Cham: Springer International Publishing, 2020.

[20] J. C. Bowen, C. P. Ward, G. W. Kling, and R. M. Cory, "Arctic amplification of global warming strengthened by sunlight oxidation of permafrost carbon to co2," *Geophysical research letters*, vol. 47, no. 12, p. n/a, 2020.

[21] Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou,

M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), "IPPC 2018: Global Warming of 1.5°C," Intergovernmental Panel On Climate Change (IPCC), 2019.

[22] United Nations Environment Programme, "Emissions Gap Report 2021: The Heat - Is On A world of climate promises not yet delivered," 2021.

[23] Miljødirektoratet, *Sirkulær økonomi*, 2021. Available: https://www.miljodirektoratet.no/ansvarsomrader/avfall/sirkular-okonomi/. Accessed: 30 April 2022.

[24] Ellen MacArthur Foundation, *Circular economy systems diagram*, 2019. Drawing based on Braungart & McDonough, Dradle to Cradle (C2C). Available: https://ellenmacarthurfoundation.org/circular-economy-diagram. Accessed: 30 April 2022.

[25] European Commission - the Directorate-General for Communication, *A European Green Deal - Striving to be the first climate-neutral continent*, n.d.. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#documents. Accessed: 30 April 2022.

[26] European Commission - the Directorate-General for Communication, *European Green Deal*, n.d.. Available: https://ec.europa.eu/clima/eu-action/european-green-deal_en. Accessed: 30 April 2022.

[27] United Nations - Department of Economic and Social Affairs, *The 17 goals*, 2020. Available: https://sdgs.un.org/goals. Accessed: 30 April 2022.

[28] United Nations, *Goal 12: Ensure sustainable consumption and production patterns*, n.d.. Available: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/. Accessed: 26 January 2022.

[29] Ø. Ihlen, *Samfunnsansvar på norsk - Tradisjon og kommunikasjon*, Bergen: Fagbokforlaget Vigmostad & Bjørke AS, 2011.

[30] United Nations Environment Programme (UNEP), "2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector," Nairobi, 2020.

[31] United Nations Statistics Division: Development Data and Outreach Branch, *Ensure sustainable consumption and production patterns*, 2022. Available: https://unstats.un.org/sdgs/report/2021/goal-12/. Accessed: 10 May 2022.

[32] United Nations Population Fund (UNEPA), *World Population Dashboard*, 2021. Available: https://www.unfpa.org/data/world-population-dashboard. Accessed: 29 April 2022.

[33] United Nations, Department of Economic And Social Affairs, Population Division, "World Population Prospect 2019 - Highlights," New York, USA, (ST/ESA/SER.A/423), 2019.

[34] United Nations, Department of Economic and Social Affairs, Population Division, "World Urbanization Prospects: The 2018 Revision," New York, USA, (ST/ESA/SER.A/420), 2019.

[35] United Nations, *Global Issues: Water*, n.d.. https://www.un.org/en/global-issues/water. Acccessed: 01 May 2022.

[36] World Health Organization, *1 in 3 people globally do not have access to safe drinking water - UNICEF, WHO*, 2019. https://www.who.int/news/item/18-06-2019-1-in-3-people-globally-do-not-have-access-to-safe-drinking-water-unicef-who. Acccessed: 01 May 2022.

[37] World Health Organization/United Nations International Children's Emergency Fund, *WHO/UNICEF Joint Monitoring Program for Water Supply and Sanitation; Global Water Supply and Sanitation Assessment 2000 Report*, WHO/UNICEF, Washington, DC, USA, 2000.

[38] Statistics Norway, *Kommunal vannforsyning*, 2021. https://www.ssb.no/natur-og-miljo/vann-og-avlop/statistikk/kommunal-vannforsyning. Acccessed: 01 May 2022.

[39] United Nations, *Ensure availability and sustainable management of water and sanitation for all* , n.d.. Available: https://sdgs.un.org/goals/goal6. Accessed: 10 May 2022.

[40] G. Ferrari, M. Miyamoto, and A. Ferrari, "New sustainable technology for recycling returned concrete," *Construction and Building Materials*, vol. 67, pp. 353–359, 2014.

[41] S. A. Miller, A. Horvath and P. J. M. Monteiro,"Impacts of booming concrete production on water resources worldwide," *Nature Sustainability*, vol. 1, no. 1, pp. 69–76, 2018. [Online]. Available: https://doi.org/10.1038/s41893-017-0009-5.

[42] *Concrete — Specification, performance, production and conformity* , NS-EN 206:2013+A2:2021+NA:2021, Standard Norge, 2021.

[43] R. Myrdal, *BETONGKJEMI - Bindemidler og tilsetningsstoffer til betong*, 2015. Available: https://docplayer.me/16472152-Betongkjemi-bindemidler-og-tilsetningsstoffer-til-betong-roar-myrdal.html. Accessed: 15 April 2022.

[44] *Aggregates for concrete*, NS-EN 12620:2002+A1:2008+NA:2016, Standard Norge, 2016.

[45] X. Zhong, S. Deetman, A. Tukker, and P. Behrens, "Increasing material efficiencies of buildings to address the global sand crisis," *Nat. Sustainability*, vol. 5, pp. 389–392, May 2022.

[46] M. S. Zafar, U. Javed, R. A. Khushnood, A. Nawaz, and T. Zafar, "Sustainable incorporation of waste granite dust as partial replacement of sand in autoclave aerated concrete," *Construction & building materials*, vol. 250, p. 118878, 2020.

[47] *Mixing water for concrete - Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete*, NS-EN 1008:2002, Standard Norge, 2002.

[48] N. Su, B. Miao, and F.-S. Liu, "Effect of wash water and underground water on properties of concrete," *Cement and concrete research*, vol. 32, no. 5, pp. 777–782, 2002.

[49] Prof. K.O. Kjellsen, "Norwegian Manufactured Cements," partly based on TKT 4215 Betongteknologi I, Prof. E. J. Sellevold 2003, unpublished, August, 2008.

[50] *Cement - Part 1: Composition, specifications and conformity criteria for common cements*, NS-EN 197-1, 2011.

[51] S. H. Kosmatka, B. Kerkhoff and W. C. Panarese, *Design and control of concrete mixtures*, 14. ed. Skokie, Illinois, USA: Portland Cement Association, 2002. [Online]. Available: https://www.researchgate.net/profile/Steven_Kosmatka/publication/284663491_Design_and_Control_of_Concrete_Mixtures/links/5655d8f908aefe619b1c5f2b.pdf.

[52] Norcem AS, *NEPD-1217-383-NO*, 2014. [Online]. Available: https://www.epd-norge.no/getfile.php/139321-1535561662/EPDer/Byggevarer/Sement/NEPD-1217-383_CEM-I--Anleggsement--CEM-I-52-5N---Industrisement--52-5R--og-Standardsement--CEM-I-42-5R---Bre 1.pdf. Accessed: XX.XX.2022.

[53] E. Worrell, L. Price, N. Martin, C. Hendriks, and L. O. Meida, "Carbon dioxide emissions from the global cement industry," *Annual review of energy and the environment*, vol. 26, no. 1, pp. 303–329, 2001. [Online]. Available: http://web.b.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=1&sid=ccd2493e-c9dd-48a0-ba18-fb41d294ff05%40pdc-v-sessmgr01.

[54] R. T. Thorstensen, "Standardgitte forutsetninger og begrensninger på bruk av annen type slagg enn GGBS i sement- og betongproduksjon for alminnelige bygge- og anleggsarbeider," C&S ENG., UiA, Norway, 002/2019, 2019.

[55] F. Sandrolini and E. Franzoni, "Waste wash water recycling in ready-mixed concrete plants," *Cement and Concrete Research*, vol. 31, no. 3, pp. 485–489, 2001.

[56] A. Iizuka, Y. Sakai, A. Yamasaki, M. Honma, Y. Hayakawa, and Y. Yanagisawa, "Bench-scale operation of a concrete sludge recycling plant," *Industrial & engineering chemistry research*, vol. 51, no. 17, pp. 6099–6104, 2012.

[57] V. W. Tam and C. M. Tam, "Economic comparison of recycling over-ordered fresh concrete: a case study approach," *Resources, Conservation and Recycling*, vol. 52, no. 2, pp. 208–218, 2007.

[58] C. V. Nielsen and M. Glavind, "Danish experiences with a decade of green concrete," *Journal of Advanced concrete technology*, vol. 5, no. 1, pp. 3–12, 2007.

[59] S. Correia, F. Souza, G. Dienstmann, and A. Segadaes, "Assessment of the recycling potential of fresh concrete waste using a factorial design of experiments," *Waste management*, vol. 29, no. 11, pp. 2886–2891, 2009.

[60] R. Rughooputh, J. O. Rana, and K. Joorawon, "Possibility of using fresh concrete waste in concrete for non structural civil engineering works as a waste management strategy," *KSCE Journal of Civil Engineering*, vol. 21, no. 1, pp. 94–99, 2017.

[61] K. Obla, H. Kim, and C. L. Lobo, "Crushed returned concrete as aggregates for new concrete," tech. rep., Citeseer, 2007.

[62] S. Correia, F. Souza, G. Dienstmann, and A. Segadaes, "Assessment of the recycling potential of fresh concrete waste using a factorial design of experiments," *Waste management*, vol. 29, no. 11, pp. 2886–2891, 2009.

[63] A. Kazaz, S. Ulubeyli, and M. Atici, "Economic viability analysis for fresh concrete waste reclaimers: The capacity of leftover concrete," *KSCE journal of civil engineering*, vol. 22, no. 1, pp. 12–23, 2017.

[64] H. K. Birkenes, Senior Advisor at Ribe Betong AS, Personal Communication by e-mail, 04 April 2022.

[65] M. Paolini and R. Khurana, "Admixtures for recycling of waste concrete," *Cement and concrete composites*, vol. 20, no. 2-3, pp. 221–229, 1998.

[66] Ribe Betong, *Ribe Blokk*, 2021. Available: https://www.ribebetong.no/ribeblokk. Accessed: 16 April 2022.

[67] Ribe Betong AS, Instagram Story, 2022. Available: https://instagram.com/stories/ribe.betong/2829891576482879417?igshid=MDJmNzVkMjY=. Accessed: 03 May 2022.

[68] R. Wang and Y. X. Zhang, "Recycling fresh concrete waste: A review," *Structural concrete : journal of the FIB*, vol. 19, no. 6, pp. 1939–1955, 2018.

[69] A. Iizuka, T. Sasaki, M. Honma, H. Yoshida, Y. Hayakawa, Y. Yanagisawa, and A. Yamasaki, "Pilot-scale operation of a concrete sludge recycling plant and simultaneous production of calcium carbonate," *Chemical engineering communications*, vol. 204, no. 1, pp. 79–85, 2017.

[70] Blascon, *preventative & curative concrete buildup removal - ReadyJet*, 2022. Available: https://blascon.com/products/mixertruck-drum-concrete-buildup-removal-and-washout/. Accessed: 07 May 2022.

[71] Blascon, *Robotic concrete removal for mixer drums*, 2022. Available: https://www.readyjet.co.uk/. Accessed: 07 May 2022.

[72] Blascon, *concrete buildup prevention - DrumJet*, 2022. Available: https://blascon.com/products/mixertruck-drum-concrete-washout/. Accessed: 07 May 2022.

[73] Blascon, *DrumJet - Robotic high pressure drum mixer cleaning*, 2020. Available: https://blascon.com/wp-content/uploads/2020/03/BLC_DrumJet_Brochure.pdf. Accessed: 07 May 2022.

[74] Velde, *Velde*, n.d.. Available: https://www.veldeas.no/. Accessed: 01 June 2022.

[75] C. J. Engelsen and T. Rise, "Vurdering av resirkulert tilslag: Egnethet i rørgrøfter," SINTEF Byggforsk, Oslo, Norway, 2019:00424, 11 April 2019. Accessed: 08 May 2022. [Online]. Available: https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/2594874/2019_00424%2BVurdering%2Bav%2Bresirkulert%2Btilslag%2Bbenyttet%2Bi%2Br%25C3%25B8rgr%25C3%25B8fter.pdf?sequence=1&isAllowed=y.

[76] DHE Inc., *Basic concrete reclaim system*, 2019. Available: https://www.dhenoble.com/Basic-Concrete-Reclaim-System. Accessed: 08 May 2022.

[77] Mapei, *Re Con Zero Evo*, 2021. Available: https://www.mapei.com/no/no/re-con-zero-evo-temaside. Accessed: 02 May 2022.

[78] H. Svensson, "Cirkulär betongballast - En laborativ utvärdering av tvättmetod för återvinning av returbetong och cementslam från betongbilar," Master's Thesis, Division of Building Materials, Faculty of Engineering, Lund University, 2021.

[79] CSI Mapei, "Case report - Re-Con Dry washing: Transforming truck mixer washing sludge into a resource material," n.d..

[80] S. Adomako, A. Heimdal, and R. T. Thorstensen, "From waste to resource–utilising residue from ready-made concrete as new aggregate," *Nordic Concrete Research*, 2021.

[81] Mapei, *Re-Con Zero Evo: how concrete becomes sustainable*, 2019. Available: https://www.mapei.com/it/en/realta-mapei/detail/re-con-zero-evo. Accessed: 02 May 2022.

[82] S.- H. Norman, Business developer environmental technology at Mapei AB Sweeden, Personal Communication by e-mail, 04 April 2022.

[83] Norsk Forening for Fjellsprengningsteknikk, "Behandling og utslipp av driftsvann fra tunnelanlegg," NFF, Norway, Teknisk Rapport 09, August 2009. Accessed: 05 April 2022. [Online]. Available: https://nff.no/wp-content/uploads/sites/2/2020/04/Teknisk-rapport-nr-9.pdf.

[84] Miljødirektoratet, "Veileder for fastsetting av innblandingssoner," M-46/2013, September 2013. Accessed :05 April 2022. [Online]. Available: https://nettarkiv.miljodirektoratet.no/hoeringer/tema.miljodirektoratet.no/Global/dokumenter/horinger/horing2013-7887_veileder.pdf.

[85] L. Henninge, N. Værøy, J. Dolven and T. Loe, "Miljørisikovurdering - Utslipp av vann fra midlertidig anleggsdrift," Oslo Kommune, Norway, PF-U-070-RA-0029, 01. March 2019. Accessed: 05 April 2022. [Online]. Available: https://www.statsforvalteren.no/contentassets/deeae741adb1442aaaa67d14a26f3e74/vedlegg-3---miljorisikovurdering-fornebubanen.pdf.

[86] I. M. Bjølseth and S. R. Lysen, "Miljørisikovurdering ferskvannsresipienter og Stjørdalsfjorden - Malvik og Stjørdal," acciona Construccion, E6RV-MUL-EV-RPT-CA#00-0020, 26 November 2019. Accessed: 05 April 2022. [Online]. Avaibale: https://www.statsforvalteren.no/contentassets/0b6ee5fb759949459b5137396b8be910/e6rv-mul-ev-rpt-ca00-0020-rev-03.pdf.

[87] C. Eckbo, "Jord hindrer spredning av giftig krom fra betong," *Aftenposten*, 23 February 2021. Available: https://www.aftenposten.no/viten/i/39JMKP/jord-hindrer-spredning-av-giftig-krom-fra-betong. Accessed: 05 April 2022.

[88] Rambøll Sweco, "Vurderinger av seksverdig krom i tunnelvann," 2018. Accessed: 05 April 2022. [Online]. Available: https://www.banenor.no/contentassets/9eac907f17454cbb9dacff4abf2df461/vedlegg-5.13-temanotat-krom-6-1.pdf.

[89] C. Eckbo, "Utlekking av treverdig og seksverdig krom fra beton," NGI rapport 20180207-01-R, 04 October 2019. Accessed: 05 April 2022. [Online]. Available: https://www.ngi.no/content/download/14977/1820916/file/20180207-01-R.PDF.

[90] Standard Norge, *Standard Norge*, 2019. Available: https://www.standard.no/toppvalg/om-oss/standard-norge/. Accessed: 30 April 2022.

[91] *Standardization and related activities - General vocabulary (ISO/IEC Guide 2:2004)*, NS-EN 45020:2006, 2007.

[92] M. McDonough, William; Braungart, "The upcycle : beyond sustainability - designing for abundance," 2013.

[93] T. Pedersen, "Inspeksjonsrapport Ryfoss Betong avd. Ryfoss: Aksjon 2016 - mineralsk industri- sement, betong og ikke-metalliske mineralprodukte," Fylkesmannen i Oppland: Miljøvernavdelingen, Vang, Norway, 2016/7995, 11 October 2016. Accessed: 09 May 2022. [Online]. Available: https://docplayer.me/62995818-Inspeksjonsrapport-ryfoss-betong-avd-ryfoss.html.

[94] Fylkesmannen i Oslo og Akershus, *Avrenning av plastfibre brukt som armering i ferdigbetong - et nytt miljøproblem*, 2016. Available: https://www.statsforvalteren.no/oslo-og-akershus/miljo-og-klima/nyheter/2016/11/avrenning-av-plastfibre-brukt-som-armering-i-ferdigbetong---et-nytt-miljoproblem/. Accessed: 09 May 2022.

[95] *Forskrift om tekniske krav til byggverk (Byggteknisk forskrift - TEK17)*, 2017.

[96] *Lov om offentlige anskaffelser (anskaffelsesloven*, 2017. [Online]. Available: https://lovdata.no/dokument/NL/lov/2016-06-17-73.

[97] Nærings- og fiskeridepartementet, *Samfunnsansvar*, 2017. Available: https://www.regjeringen.no/no/tema/naringsliv/konkurransepolitikk/offentlige-anskaffelser-/andre-kolonne/samfunnsansvar/id2518748/. Accessed: 14 May 2022.

[98] Norsk betongforening, *nr. 37 Lavkarbonbetong (NB37)*, 2020. Oslo: Norsk Betongforening.

[99] E. Wæhle, S. Dahlum and S. Grønmo, "case-studie," in *Store norske leksikon*, 2009. [Online]. Available: https://snl.no/case-studie, Accessed: 02 May 2022.

[100] R. K. Yin, *Case study research: design and methods*, 5th ed.. Los Angeles, California, USA: SAGE, 2014.

[101] Ribe Betong AS, *Hele Sørlandets Betongleverandør*, n. d. Available: https://www.ribebetong.no/. Accessed: 14 March 2022.

[102] K. K. Przyworska, Control Manager at Ribe Betong AS, Personal Communication by e-mail, 15 March 2022.

[103] I. Stenbråten, KS-HMS & Ytre Miljø at Ribe Betong As, Personal Communication by e-mail, 27 April 2022.

[104] Ø. Mortensvik, Technology Manager at Ribe Betong AS, Personal Communication by SMS, 25 May 2022.

[105] Ribe Betong AS, *Bærekraft*, n. d. Available: https://www.ribebetong.no/barekraft. Accessed: 14 March 2022.

[106] *Environmental management systems - Requirements with guidance for use*, NS-EN ISO 14001:2015, Standard Norge, 2015.

[107] A. Verma, Communication consultant and transport coordinator at Ribe Betong AS, Personal Communication by e-mail, 01 June 2022.

[108] FABEKO, *Vaske- og sedimentasjonsanlegg i endring*, 2021. Available: https://fabeko.no/2021/09/15/vaske-og-sedimentasjonsanlegg-i-endring. Accessed: 21 May 2022.

[109] S.-H. Isaksen, Department manager at Ribe Betong, Personal Communication by e-mail, 21 April 2022.

[110] H. Baumann and A.-M. Tillman, *The Hitch Hiker's Guide to LCA: An orientation in life cycle assessment methodology and application.* Lund, Sweeden: Studentlitteratur, 2004.

[111] D. Caro, "Carbon Footprint," in *Encyclopedia of Ecology*, 2 ed. B.Fath, Ed. Elsevier B.V., 2019, pp. 252-257. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780124095489107523.

[112] University of Agder, *Life cycle assessment*, n. d. Available: https://grimstad.uia.no/puls/climatechange/nns05/13nns05a.htm. Accessed: 20 February 2022.

[113] *Environmental management - Life cycle assessment - Principles and framework*, NS-EN ISO 14040:2006, Standard Norge, 2006.

[114] G. Itskos, N. Nikolopoulos, D.-S. Kourkoumpas, A. Koutsianos, I. Violidakis, P. Drosatos, and P. Grammelis, "Chapter 6 - energy and the environment," in *Environment and Development* (S. G. Poulopoulos and V. J. Inglezakis, eds.), pp. 363–452, Amsterdam: Elsevier, 2016.

[115] M. A. Curran, "Overview of Goal and Scope Definition in Life Cycle Assessment," in *Goal and Scope Definition in Life Cycle Assessment. LCA Compendium - The Complete World of Life Cycle Assessment*, M. A. Curran, Ed. Springer, Dordrecht, 2017. [Online]. Available: https://doi.org/10.1007/978-94-024-0855-3_1.

[116] M. Finkbeiner, R. Ackermann, V. Bach, M. Berger, G. Brankatschk, Y.-J. Chang, M. Grinberg, A. Lehmann, J. Martínez-Blanco, N. Minkov, S. Neugebauer, R. Scheumann, L. Schneider, and K. Wolf, "Challenges in life cycle assessment: An overview of current gaps and research needs," in *Background and Future Prospects in Life Cycle Assessment*, LCA Compendium – The Complete World of Life Cycle Assessment, pp. 207–258, Dordrecht: Springer Netherlands, 2014.

[117] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, "Life cycle assessment (lca) and life cycle energy analysis (lcea) of buildings and the building sector: A review," *Renewable & sustainable energy reviews*, vol. 29, pp. 394–416, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032113005777?via%3Dihub#bib15.

[118] W. Xing, V. W. Tam, K. N. Le, J. L. Hao, and J. Wang, "Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review," *Construction and Building Materials*, vol. 317, p. 125950, 2022.

[119] A. Di Maria, J. Eyckmans, and K. Van Acker, "Downcycling versus recycling of construction and demolition waste: Combining lca and lcc to support sustainable policy making," *Waste Management*, vol. 75, pp. 3–21, 2018.

[120] P. Frontera, A. Malara, and M. Mistretta, "Recent trends in sustainability assessment of "green concrete"," in *New Metropolitan Perspectives*, Smart Innovation, Systems and Technologies, pp. 1402–1412, Cham: Springer International Publishing, 2020.

[121] Mapei AS, *Våre produkter*, 2021. Available: https://www.mapei.com/no/no/produkter-og-systemlosninger/produktliste. Accessed: 19 April 2022.

[122] K. Fagerheim, Trainee at Mapei Nordic, Personal Communication by e-mail, 28 April 2022.

[123] Norcem, *Bygg- og anleggsementer*, n.d.. Available: https://www.norcem.no/no/BA-sementer. Accessed: 04 May 2022.

[124] Norcem, *Flygeaske*, n.d.. Available: https://www.norcem.no/no/FlyAsh. Accessed: 04 May 2022.

[125] Tor.- M. Zachariassen, Concrete Technologist at Norcem Brevik, Personal Communication by e-mail, 04 May 2022.

[126] Google, *Google Maps*, 2022. Available: https://www.google.com/maps.

[127] Available: https://www.epd-norge.no/ferdig-betong/b20-m90-d22-synk-200-article1612-317.html. Accessed: 12 May 2022.

[128] D. Silva, A. O. Nunes, A. da Silva Moris, C. Moro, and T. O. R. Piekarski, "How important is the lca software tool you choose comparative results from gabi, openlca, simapro and umberto," in *Proceedings of the VII Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica, Medellin, Colombia*, pp. 10–15, 2017.

[129] ecoinvent, *Allocation at the Point of Substitution*, n.d. Available: https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/apos-system-model/allocation-at-the-point-of-substitution.html. Accessed: 1 April 2022.

[130] M. Z. Hauschild and M. A. Huijbregts, "Introducing life cycle impact assessment," in *Life cycle impact assessment*, pp. 1–16, Springer, 2015.

[131] Huijbregts, M.A.J, Steinmann, Z.J.N, Elshout, P.M.F, Stam, G, Verones, F, Vieira, M, Zijp, M, Hollander, A and Zelm, R. van, "ReCiPe 2016 v1.1 - A harmonized life cycle impact assessment method at midpoint and endpoint level - Report I: Characterization," National Institute for Public Health and the Environment, The Netherlands, RIVM Report 2016-0104a, 2017. Accessed: 25 May 2022. [Online]. Available: https://pre-sustainability.com/legacy/download/Report_ReCiPe_2017.pdf.

[132] Various authors, PRé Sustainability, *SimaPro database manual - Methods library*, 2020. Available: https: //simapro.com/wp-content/uploads/2020/10/DatabaseManualMethods.pdf. Accessed: 1 April 2022.

[133] K. P. Shine, J. S. Fuglestvedt, K. Hailemariam, and N. Stuber, "Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases," *Climatic change*, vol. 68, no. 3, pp. 281–302, 2005.

[134] Intergovernmental Panel on Climate Change, *IPCC Fourth Assessment Report: Climate Change 2007.* [Online]. https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-2-5.html. Accessed: 01 April 2022.

[135] J. P. Toldnæs, "globale oppvarmingspotensialer," in *Store Norske Leksikon*, 2022. [Online]. https://snl.no/globale_oppvarmingspotensialer. Accessed: 01 April 2022.

[136] J. Kjensmo and Dr. D. Hongve, "eutrofiering," in *Store Norske Leksikon*, 2022. [Online]. https://snl.no/eutrofiering. Accessed: 29 May 2022.

[137] The Editors of Encyclopedia Britannica, "eutrophication," in *Encyclopedia Britannica*, n.d.. [Online]. Available: https://www.britannica.com/science/eutrophication, Accessed: 03 June 2022.

[138] H.-L. Pesonen, T. Ekvall, G. Fleischer, G. Huppes, C. Jahn, Z. S. Klos, G. Rebitzer, G. W. Sonnemann, A. Tintinelli, B. P. Weidema, *et al.*, "Framework for scenario development in lca," *The International Journal of Life Cycle Assessment*, vol. 5, no. 1, pp. 21–30, 2000.

[139] Mapei, *Re Con Zero Evo: To-komponent pulvertilsetning for gjenvinning av restbetong fra betongbiler*, n.d.. Available: https://cdnmedia.mapei.com/docs/librariesprovider60/products-documents/1_6946-reconzeroevo-no_03a5c4aa768b48feb59545691d1d1d0e.pdf?sfvrsn=1352ddcb_0. Accessed: 02 May 2022.

[140] Ø. Mortensvik, Technology Manager at Ribe Betong AS, Personal Communication by e-mail, 22 May 2022.

[141] Ø. Mortensvik, Technology Manager at Ribe Betong AS, Personal Communication by e-mail, 15 February 2022.

[142] Ringknuten Pukkverk AS, *Samsvarserklæringer og deklarasjoner*, n. d. Available: https://www.ringknuten.no/newpage. Accessed: 14 March 2022.

[143] Vegdirektoratet, *Statens vegvesen - Håndbok R210 Laboratorieundersøkelser*, 2016. [Online]. Available: https://www.vegvesen.no/globalassets/fag/handboker/hb-r210-laboratorieundersokelser-2016.pdf.

[144] H. Ge, A. Sha, Z. Han, and X. Xiong, "Three-dimensional characterization of morphology and abrasion decay laws for coarse aggregates," *Construction & building materials*, vol. 188, pp. 58–67, 2018.

[145] *Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation*, NS-EN 1097-2:2020, Standard Norge, 2020.

[146] S. Adomako, C. J. Engelsen, R. T. Thorstensen, and D. M. Barbieri, "Review of the relationship between aggregates geology and los angeles and micro-deval tests," *Bulletin of engineering geology and the environment*, vol. 80, no. 3, pp. 1963–1980, 2021. [Online]. Available: https://doi.org/10.1007/s10064-020-02097-y.

[147] R. C. Pettersen, "Oppgaveskrivingens abc : veileder og førstehjelp for høgskolestudenter," 2008.

[148] G. A. Pedersen and R. J. Reidunsdatter, *Litteraturstudie som metode*, 2018. Available: https://www.youtube.com/watch?v=KF3PtpaDsm8. Accessed: 06 May 2022.

[149] H. Aveyard, *Doing a literature review in health and social care: a practical guide*, 2nd ed. Maidenhead: McGraw-Hill/Open University Press, 2014.

[150] C. Forsberg, "Att göra systematiska litteraturstudier : värdering, analys och presentation av omvårdnadsforskning," 2013.

[151] University of Copenhagen & Technical University of Denmark (DTU), *Academic Information Seeking*, 2020. Available: https://www.coursera.org/learn/academicinfoseek/home/welcome.

[152] Unit, *Oria søketjeneste*, 2020. Available: https://www.unit.no/tjenester/oria-soketjeneste. Accessed: 06 May 2022.

[153] Google, *About Google Scholar*, n.d.. Available: https://scholar.google.com/intl/en/scholar/about.html. Accessed: 06 May 2022.

[154] Google, *Google Search*, 2020. Available: https://www.google.com/. Accessed: 06 May 2022.

[155] Standard Norge, *Standard Norge*, n.d.. Available: https://www.standard.no/. Accessed: 07 May 2022.

[156] B. Pedersen, "Effekt av tilslag på betongens mekaniske egenskaper - Trykkfasthet, E-modul og spaltestrekkfasthet," Statens Vegvesen, No. 181, January 2019. Accessed: 05 May 2022. [Online]. Available: https://vegvesen.brage.unit.no/vegvesen-xmlui/bitstream/handle/11250/2580688/Effekt%20av%20tilslag%20p%C3%A5%20betongens%20mekaniske%20egenskaper%20SVV%20rapport%20181%20%2811%20MB%29.pdf?sequence=1&isAllowed=y.

[157] FABEKO, "FABEKOs forslag til normverdier for innholdet i utslippsvann fra betongfabrikk," 2018 https://fabeko.no/download/fabekos-forslag-til-normverdier-for-innholdet-i-utslippsvann-fra-betongfabrikk/?wpdmdl=3281&refresh=628145708e9a01652639088&ind=1589299781934&filename=Normverdier_utslippsvann_2018.pdf.

[158] *Lov om vern mot forurensninger og om avfall (forurensningsloven)*, 2021. [Online]. Available: https://lovdata.no/dokument/NL/lov/1981-03-13-6#KAPITTEL_3.

[159] *Forskrift om gjenvinning og behandling av avfall (avfallsforskriften)*, 2022. Available: https://lovdata.no/dokument/SF/forskrift/2004-06-01-930.

[160] Norwegian Environment Agency, "Høring av forslag til nytt kapittel i forurensningsforskriften - forurensning fra betongproduksjon," NEA, n.d.. [Online]. Available: https://hss.miljodirektoratet.no/api/1/publisert/hoering/vedlegg/17015. Accessed: 02 June 2022.

[161] *Vedlegg 1 forslag til forskrift for betongproduksjon*, 2021. [Online]. Available: https://hss.miljodirektoratet.no/api/1/publisert/hoering/vedlegg/17016.

Appendices

Appendix 01 - Poster

Appendix 02 - Electricity Use at Ribe Betong 2021

Appendix 03 - Water Usage Ribe Betong 2021

Appendix 04 - Transport Distance Materials Ribe Betong

Appendix 05 - Ribe Blokks

Appendix 06 - Materials SimaPro

Appendix 07 - Scenario Analysis

Appendix 08 - Literature Log

Appendix 09 - Calculation of LA Value 10.0-14.0 mm

Appendix 10 – LCA Results

Appendix 11 - Process Flow Diagrams

Appendix 12 - Process Flow Diagrams Eutrophication

Appendix 13 - Scenario Analysis Results

Master

UiA University of Agder

Master's thesis

Faculty of Engineering and Science

Department of Engineering Sciences