Investigating the potential of CO$_2$ sequestration in concrete through natural and accelerated carbonation

An analysis of natural and accelerated CO$_2$ sequestration in million program areas in the municipality of Gothenburg - a case study

Master's thesis in Industrial Ecology

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Abstract

This thesis explores the potential End-of-Life (EoL) management of demolished concrete from Million Program buildings (MP) to act as a carbon sink through the process of natural and accelerated carbonation. The study presents speculative scenarios, natural carbonation in stockpiles and the use of accelerated carbonation through a fluidized bed unit, which involves the utilization of flue gases to enhance the carbon sequestration of concrete aggregates (CA). A significant amount of CO_2 is sequestrated in the service life of a building but the largest potential is at the EoL, where the study indicates that concrete can reabsorb between 11.1-55.5 % of CO_2 emissions from cement production. This is when accounting for process emissions related to transporting, crushing and using loaders to move the concrete into stockpiles. The thesis suggests the need for more processing sites and optimized stockpile dimensions to maximize carbon uptake. The thesis also highlights the complexity of the carbonation process and calls for further studies to accurately determine the carbonation degree and operational planning for CO_2 sequestration in concrete aggregates. The research underscores the importance of natural carbonation and its role in reducing the carbon footprint of concrete.

Acknowledgements

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CA	Concrete Aggregates
DoC	Degree of Carbonation
EoL	End-of-life
IS	Industrial symbiosis
MP	Million Program

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Introduction

Human activities, marked by the widespread use of fossil fuels, deforestation, and land use, have resulted in a substantial increase in the levels of greenhouse gases in the earth's atmosphere, which is a driving force behind climate change. The pressing global challenges of climate change have underscored the need for innovative and sustainable solutions to mitigate greenhouse gas emissions, and to focus on sectors that contribute significantly to these can have a large positive impact if successfully implemented. The built environment, shaped by construction and demolition activities, contributes substantially to CO_2 emissions and is one of the leading contributors to climate change in Europe (Antunes et al., 2024). The construction industry is resource-intensive with extensive use of energy-demanding materials, such as concrete. Concrete is the most common building material in the world, with 30 billion tons used annually (Huang et al., 2020; Nature, 2021). Chaudhury et al. (2023) explains that concrete production alone contributes approximately 7% of global CO_2 emissions yearly, emphasizing the urgency of research on how to reduce its environmental impact, and more so since its demand increases more than for other building materials such as steel and wood; see figure 1. To limit global warming to 1.5 °C,
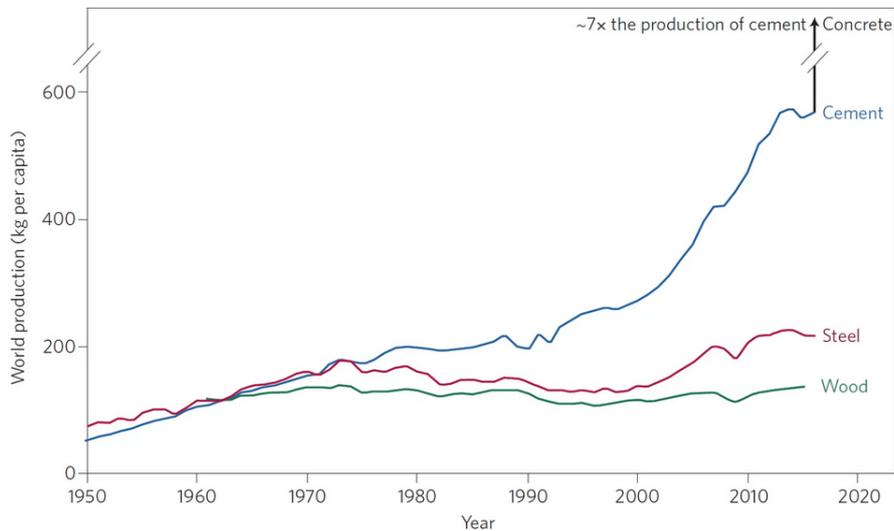
Figure 1: World production in kg per capita of cement, steel, and wood between 1950-2015 (Monteiro et al., 2017).

which is the target set forth in the Paris Agreement, there is a need to reduce anthropogenic greenhouse gas emissions. However, many climate scientists don't believe that emission reduction alone will be enough to limit global warming to 1.5 °C, there

is a need for complementary technologies to allow for a needed drastic reduction of atmospheric greenhouse gases and emissions (Plumer and Popovich, 2021; UNECE, 2015). A potential strategy is to expand the focus beyond emission reduction and explore carbon capture through *carbonation*, a natural process that uses concrete as a carbon sink. Carbonation occurs when CO_2 from the atmosphere reacts with calcium hydroxide $(Ca(OH)_2)$ in the concrete to form calcium carbonate $(CaCO_3)$, a process that occurs naturally over time (Andersson et al., 2013). However, the natural carbonation of concrete can be a slow process, that takes place over months to years, but with large stocks of concrete in society the total amount of sequestrated CO_2 can be significant over time. Urbanization has led to large amounts of concrete in cities, making cities a natural focal point for the role it plays in (Holcim, 2023; SCB, 2015; Sika, n.d.).

During the 1960s and 1970s, more than 1.6 million homes were built in Sweden to combat a housing crisis during a time of great economic development (SCB, 2023). At its peak from 1965-1974, a period that came to be known as the *million program*, more than 100'000 homes were completed annually. With cities expanding and utilizing concrete for buildings, tunnels and bridges the stock of concrete only increases. An initial literature review was conducted in an attempt to find gaps in the studied area from which research questions could grow. The chemical reaction of carbonisation has long been a known phenomenon due to its adverse effects on reinforcement in concrete. However, traction regarding utilizing concrete as a carbon sink has grown over the past decade which will be the focus of this study. From the literature review, it was observed that there was a lack of research on the subject of accelerated carbonation methods applied on industrial scales. Most studies conducted tests in laboratory settings and on low volumes of aggregates. One project stood out as it had undergone laboratory tests on accelerated carbonation before installing a pilot-project on a cement plant in France that handled volumes on an industrial scale (Torrenti et al., 2022). Other accelerated carbonation methods included carbon curing, which is out of the scope of this study as it delves into the carbonisation in the production phase and not in the end of life (EoL) (Šavija and Luković, 2016; Shang et al., 2023. Moreover, the geographical scopes on the initial literature review were mainly on northern European countries while the rest weren't specific in their spatial locations (Ammenberg et al., 2014; Lagerblad, 2005; Patricio et al., 2017; Yu et al., 2021).

The concept industrial symbiosis (IS) was of interest too investigate, mainly the utilization of flue gases from industries as an output and carbonisation of crushed concrete as an input. The concept of IS was observed in two studies, Patricio et al. (2017) and Van Oss and Padovani (2003), in the initial literature review but weren't exploring the option of flue gas utilization. Overall, it could be observed that there was a gap in exploring IS alongside accelerated carbonation which is of interest to be explored within the context of Gothenburg municipality.

1.1   Aim

This report aims to quantify the natural carbon capture potential of demolished concrete, and to compare this to an accelerated carbonation technology. This is done through a case study in which the source of concrete is million program buildings built between 1965-1974 in the municipality of Gothenburg.

1.2   Research questions

- Where are the buildings within the scope of this study located, when will they be demolished and how much CO_2 can naturally be bound in demolished concrete from buildings constructed between 1965-1974 in the municipality of Gothenburg?

- What could a system for the carbonation of concrete in Gothenburg look like?

- What are the net emissions from processing concrete to be leveraged as a carbon sink via natural and accelerated carbonation?

2
Background

2.1 Production, emissions and waste management of concrete

Concrete is a mixture of three main components: aggregates, cement and water. Aggregates form the bulk and provide the structural backbone of concrete. The aggregates vary in size, ranging from fine sand particles to coarse gravel or crushed stone. The selection and size variation of aggregates are essential to ensure proper packing and interlocking within the concrete matrix. This, in turn, influences the density, workability, and strength of the concrete. Cement is a binding agent that holds the aggregates together. When mixed with water, cement undergoes a chemical reaction called hydration, forming a paste that coats and surrounds the aggregate particles. As this paste hardens and cures, it provides the concrete with its compressive strength. Over time, the strength of concrete increases as the hydration process continues. The production of cement involves extracting limestone rock from the lithosphere. Limestone, primarily composed of calcium carbonate, undergoes a series of steps to become cement. After extraction, the limestone is crushed and transported to a cement kiln. Inside the kiln, the limestone is heated to temperatures reaching 1450 °C, initiating a process known as calcination. During calcination, the limestone undergoes chemical decomposition, releasing carbon dioxide and leaving behind calcium oxide (lime, CaO). CaO reacts with other minerals present in the raw materials to form clinker, the main component of cement. The clinker is then finely ground to produce the powdered cement used in concrete production (PCA, n.d.).

2.1.1 Calcination- and fuel emissions

The main constituents of clinker are alumina (Al_2O_3), iron oxide (Fe_2O_3), lime (CaO) and silica (SiO_2). According to Tokheim (1999) a typical clinker would constitute 66% CaO, 21% SiO_2, 5% Al_2O_3, 3% Fe_2O_3 and 5% of other materials. When heated, a number of complex chemical reactions occur which will not be explored in detail in this study. In short, four compounds are formed that in cement chemist notation are Dicalcium silicate (C_2S), Tricalcium silicate (C_3S), Tricalcium aluminate (C_3A) and Tetracalcium alumino ferrite (C_4AF). These four compounds are all important for the properties of the cement and affect aestethics, durability, strength development, and heat evolution of the cement. Without the addition of iron and aluminum compounds the calcination would take place at temperatures of more

than 3000 °C (Munthe, 2013). Depending on the chemical composition and internal proportion of these four compounds in the quarried raw material, varying additives are added to compensate for variations and to create the desired properties of the cement (Britannica, n.d.).

The calcination of limestone is an endothermic reaction, requiring approximately 1.7 MJ per kg of $CaCO_3$ (Kahawalage et al., 2017). The calcination of $CaCO_3$ can be expressed by the following chemical reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$
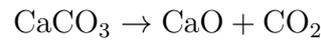
CO_2 is an inherent by-product when producing clinker, and the emission-to-production ratio is in the range of 600-900 kg of CO_2 / tons of cement produced, depending on the ratio between the clinker and the cement and the type of fuel used for heating. Approximately 2/3 of production emissions derive from the calcination process and 1/3 from burning fuel to heat the kiln.

2.1.2 Contemporary post-demolition management of concrete

Understanding today's system of waste handling is imperative to shape and improve a more sustainable practice of managing the vast amounts of concrete waste generated from construction activities. By utilizing demolished concrete as or in a secondary product, the demand for virgin materials can be reduced, aligning with national and global climate goals of reducing the extraction of natural resources (Boverket, n.d.).

When tearing down a concrete structure, the concrete is broken down into transportable pieces for intermediate stockpiling before the removal of steel reinforcement. Once further processed into smaller fractions, fresh uncarbonated surfaces of the concrete react with CO_2 to enable further carbonation. Once at a processing site, the steel reinforcement is removed from the concrete and awaits further processing, these masses of crushed concrete are placed into stockpiles. The mixed fractions generated from the retrieval of reinforcement are placed in a stockpile which creates subpar conditions for carbon uptake, especially when exposed to rain which further compacts the stockpile, resulting in poor airflow and thus the carbonation rate (SIS, 2019). by stockpiling in similar fractions, more void space is created and thus increased airflow for a more efficient carbonation. See figure 5.

With the current waste handling system in place, the conditions for carbonation is relatively low which means there is a potential for improvement in the CO_2 uptake for waste concrete (Munthe, 2013).

The current waste handling system in Sweden is described by Munthe (2013) in 5 steps:

1. Demolition of used concrete products
2. Intermediate stockpiling of demolished concrete (storage 0.5 - 4 years)
3. Rebars are extracted for recycling and the crushed concrete is piled with mixed fractions.
4. Intermediate stockpiling of mixed concrete fractions (storage 1-4 months)
5. The mixed concrete is used in construction applications such as landfillings, road base coarse, or building foundations.

According to Stripple et al. (2018) a significant amount of the cement paste (20%) turns into fine dust during the processes of crushing and fractioning. With proper handling, these fine particles of hydrated cement can carbonate quickly in a couple of days or up to a few weeks. However, the amount of fine dust depends on equipment and crushing practices which may vary.

2.2 Carbonation

Carbonation refers to the chemical process where atmospheric CO_2 diffuses into the concrete and reacts with calcium hydroxide and calcium silicate hydrates (CSH) present in the pore surface of the hardened cement paste, resulting in the formation of limestone i.e. calcium carbonate ($CaCO_3$) (Andersson et al., 2013). This chemical reaction binds the CO_2, effectively acting as a permanent carbon sink. The chemical reaction is represented as follows:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$
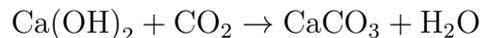
CO_2 initially penetrates the concrete at the surface by a number of chemical reactions, driven mainly by gas diffusion in the concrete pores and proceeds inwards the concrete element (Silva et al., 2015). There is an increase in density as $CaCO_3$ is formed in the pores resulting in a reduction of water adsorption Zhang et al. (2020). The carbonation process needs moisture to be initiated as it's in water where CO_2 is dissolved into carbonate ions which react with calcium ions to form calcite. To summarise, the sequestration of CO_2 involves three phases Li and Wu, 2022. The theoretical binding capacity is dictated by the amount of CaO in the portland clinker that can bind back CO_2, i.e, the amount of CO_2 that was released during calcination (SIS, 2019). Portland cement is 95 % clinker which consists of 65% CaO that may potentially react with CO_2. For Portland cement type CEM-I this is typically set to 0.49 kg CO_2 / kg portland cement due to the molecular compositions. As showcased in SIS (2019), the molecular weights for the given elements are as follows:

- Carbon (C): 12
- Oxygen (O): 16
- Carbon dioxide (CO_2): 44
- Calcium (Ca): 40
- Calcium oxide (CaO): 56
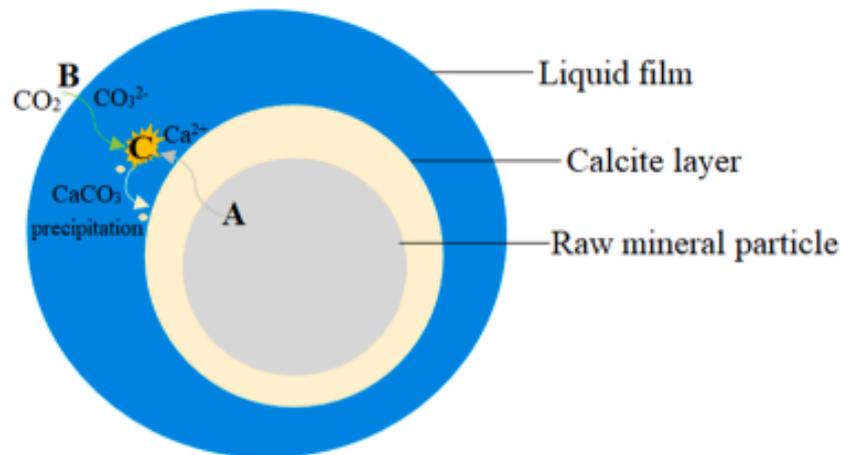
Figure 2: Visual description the carbonation reaction on a concrete aggregate(Li and Wu, 2022).

- Calcium carbonate ($CaCO_3$): $40 + 12 + (3 \times 16) = 100$

1.00 kg Portland cement thus has the potential to bind:

1.00 X 0.95 X 0.65 = 0.62 CaO
0.62 X [44/56] = 0.49 kg CO_2

This value is at the same time a way to define the degree of carbonation (DoC) (SIS, 2019) as it puts CO_2 released from calcination in relation to what it potentially can bind back. In theory, the amount of released CO_2 from calcination may bind back into the cement paste(Andersson et al., 2013) but is according to the literature often given a value of 75 %. In practicality, the carbonation is dictated by several factors (Stripple et al., 2018).

To summarize, carbonation is a chemical process where carbon dioxide from the air reacts with calcium hydroxide in the cement paste to for calcium carbonate, which reduces the alkalinity of the concrete. This occurs via diffusion in the cement paste and not the aggregates (sand and gravel). Accelerated carbonation may be achieved by increasing the surface area of concrete by crushing it and exposing more of the $Ca(OH)_2$ in the cement paste to catalyze the sequestration. Thus, the management of crushed concrete plays a significant role in leveraging the crushed concrete as a carbon sink.

2.2.1 Estimating carbonation

A way to measure the DoC is by applying phenolphthalein, a substance that changes colour corresponding to the pH on the applied surface SIS, 2019. For non-carbonated

areas it appears pink and for carbonated it is transparent Bui et al., 2023. The different levels of carbonation can be measured via image analysis where the carbonated areas (appears colorless) are divided by the fresh uncarbonated (appears pink) area to get the DoC. The advantage of this method is that its uncomplicated, relatively time efficient and economically beneficial compared to other methods. mentioned drawbacks regarding this method are that partially carbonated areas are hard to observe and that the phenolphtalein only measures the change in pH which indicates carbonation but doesn't measure the actual uptake of CO_2. Overall, the task of calculating CO_2-sequestration is complicated as there is a lack of a definitive method.

2.2.2 Conditions for carbon uptake

As explained in SIS (2019) there is no single general formula calculating CO_2 uptake that is applicable for all concrete structures in all environments as there are many parameters taken into account. A good understanding of preferable conditions for carbon sequestration is necessary to evaluate post-demolition management of concrete.

Time is one important aspect as carbonation is a slow process, a process which Lagerblad (2005) means occurs primarily during the first 50 years of a structure's lifetime. Carbonation is a surface phenomenon which slows down as it becomes progressively harder for CO_2 to penetrate and reach uncarbonated surfaces in the interior of the concrete. The carbonation rate describes the correlation between the time and depth of the transportation of carbon dioxide in concrete (SIS, 2019). Transportation effects and reactions are described by the carbonation rate "k" and permits the degree of carbonation (DOC) to be calculated at any given time. Notably, the carbonation rate is affected by several factors such as dimensions and interconnectivity of the pores, cement type and RH. Through laboratory tests, it has been established that the DOC is around 75% but present-day management of demolished concrete prohibits it from reaching those values and are instead much lower which further adds weight to explore EoL options to optimize the carbon sequestration (Andersson et al., 2019).

Water is necessary as it enables the formation of ions which react with carbon hydroxide or CSH to bind CO_2. This is why very dry concrete doesn't carbonate and reversely, in very wet concrete carbonation is instead slowed down as gas diffusion isn't enabled. For a normal dry concrete with a RH of 50 – 80 % gas diffusion is the driving mechanism where the partial pressure between the surface of the concrete and the interior dictates the carbonation level. In SIS (2019) it was evident that a RH in the air of 60% was deemed optimal for carbonation . In Gothenburg, the RH varies during the year and reaches its maximum in December at 85%, its lowest in May at 62% and with an average annual RH of 75 %.

There is a correlation between compressive strength, water/cement ratio, and carbonation rate. A higher compressive strength indicates a lower w/c ratio which

lowers the permeability for CO_2 diffusion. The amount of cement doesn't dictate the carbonation rate. The carbonation rate is higher in urban areas and indoor environments. This is due to the higher-than-average partial pressure of CO_2. Equation 1 is generally accepted (Pade and Guimaraes, 2007) as a good approximation to calculate the carbonation depth where t is time and k the carbonation rate:

$$(1) \qquad d_c = k \cdot \sqrt{t}$$

Pade and Guimaraes (2007) summarized several studies on carbonation rate and exposure conditions and concluded that the carbonation rate typically is accelerated in indoor conditions, in comparison to outdoors, as the carbonation is affected by humidity levels. In this study, carbonation was found to be most effective at a relative humidity (RH) of 40-80%. Low RH prohibits CO_2 from dissolving with the water in the pores and in contrast, in environments with too much water, e.g. submerged concrete, the permeation of CO_2 will be slowed down. Equation 2 as described in SIS (2019), is used to calculate the carbon uptake in kg CO_2 / m^2:

$$(2) \qquad C_u = (k \cdot \text{DOC}) \left(\frac{\sqrt{t}}{1000} \right) \cdot U_{tcc} \cdot C$$

k is the carbonation rate in mm/$\sqrt{t}$, DOC the degree of carbonation about the surface and t is service life. U_{tcc} is the theoretical uptake of CO_2 / kg in cement and the value for portland cement (CEM-I) is 0.49. C is cement content in kg / m^3 concrete. The result is then divided by the volume of the studied concrete to obtain a value on sequestered concrete during a buildings service life inkg CO_2 / m^3. In addition to this, a decrease in carbonation rate by 30-50 % can be expected if the concrete surfaces are covered. Exact rate depends on the thickness and properties of the cover.

"CEM" is the notation that refers to the European standard EN 197-1 that describes the proportions of different components in various types of cement in percentages (SIS, 2019). Historically, CEM-I has been the most common type of cement used in Sweden up until the 2000s (Andersson et al., 2013). For this type of cement, the portland clinker ratio is typically 95-100% of the mass ratio, whereas other cement types substitute some of the clinker with, e.g., furnace slag and fly ash, resulting in a lower clinker-to-mass ratio (Bäckman, 2022). This has been the trend since the turn of the century, where CEM-II has been more widely adopted in Europe for buildings which constitute of a lower rate of clinker and more substitutes (SIS, 2019).

2.3 Demolition

The European Union recognizes the inherent potential environmental improvements by recycling concrete & demolition waste (CDW) and established in 2020 a waste directive framework with a target of recovering 70% non-hazardous CDW for recycling or re-use. Generally, the most common use of recovered demolition waste is as filler in road construction or as backfilling material. These utilisations often subceeds the original quality of the materials, subsequently lowering the market value of them as a secondary material compared to the original one. Due to this, it is not deemed optimal in a circular perspective nor is it as efficient in substituting materials as it could be and therefore the overall environmental performance could be improved Caro et al., 2024. The studied buildings within the municipality of Gothenburg all have data on concrete quantity, but on average this constitutes 24% of CDW on average in the EU. Demolition and collective practices plays a vital role in how much concrete is recovered and although the technology exists, there are other barriers that prevent use of recovered materials as a secondary product. Identified obstacles are:

- Perceived expense of recovering and recycling in contrast to landfilling
- Low demand amongst buyers
- Regulatory challenges e.g. safety requirements
- Chemical compositions
- Competition with low-cost products stemming from virgin resources which may be cheaper

Essentially, products from primary materials don't necessarily factor in external costs such as pollution or resource depletion which are often borne by society or the environment rather than the producer.

The amount of concrete that will be available for processing will thus depend on how much is recovered from a demolition and the purity of the waste as only the concrete is of interest in a carbonation perspective. Some concrete elements may be salvageable and re-used which should be a priority according to the Swedish planning and construction law ("Riva, återvinna och återbruka – Boverket", n.d.). Thus, not all concrete may be crushed and utilized for carbonation. However, this study aims to analyze the carbonation potential if all concrete where to be utilized for carbonation.

2.3.1 Particle sizes

Aggregates are a necessity for working infrastructure in society as it serves in many vital structures such as roads, railways, docks, airports, hospitals, residential buildings and many more areas of usage (Bergmaterialindustrin, 2019). The size of the aggregates varies depending on the application, of which a few are presented below as described by ("Grus, makadam, stenmjöl och bergkross — NCC" (n.d.)):

Stone meal: 0/2 or 0/4 mm are very fine fractions and can be used for adjustments and hardening of walking paths, driveways and football fields.

Ungraded crushed rock: Coarser material with finer fractions included. Fractions such as 0/16, 0/32 and 0/90. These can serve as sub-base road layers and foundation layers.

2.4   Methods for CO_2 sequestration

2.4.1   Optimizing natural carbonation of RCA

One alternative for increasing the carbon sequestration in concrete aggregates (CA) without applying any new technologies is by changing the way the aggregates are stockpiled at the end-of-life. Knowledge of conditions for optimizing storage of CA is essential to leverage it as a carbon sink. As shown in figure 3, the largest carbonation potential is evidently to be leveraged once the concrete is demolished into smaller fractions.
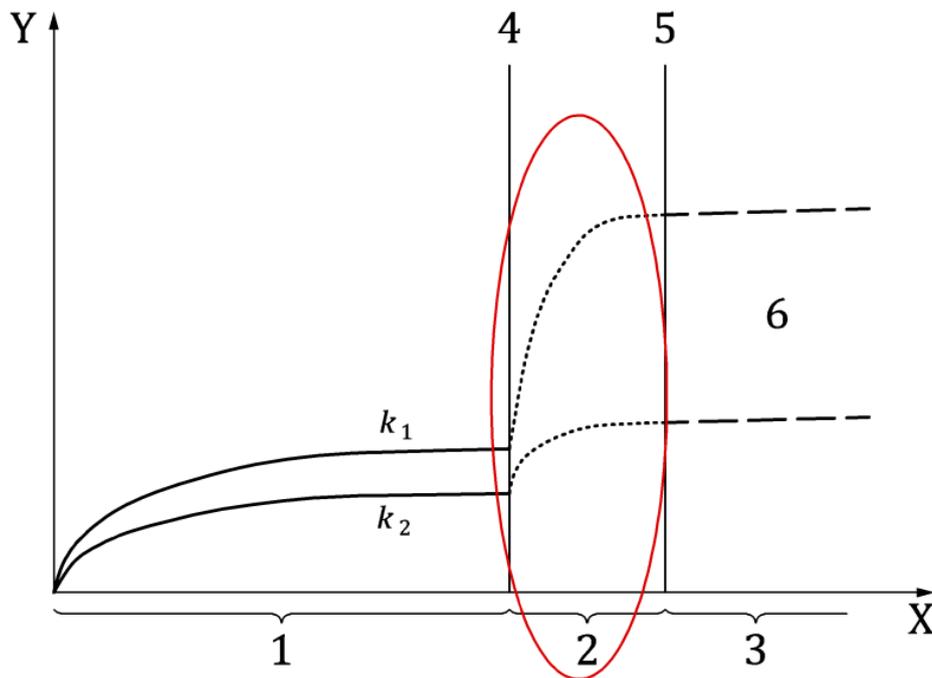
Figure 3: X-axis displays the service life of the concrete and Y-axis the relative carbonation potential. The largest potential is showcased in the waste handling stage (SIS, 2019).

These conditions were researched in a recycling center in Topinoja, Finland Skanska Finland and Toni Kekkonen Betoni (2023)to identify improvements in how the CA are stockpiled. Four piles with CA in the fractions 0-90 mm and 20-90 were measured for 14 months by their carbon dioxide concentrations, and humidity, within

the pile at 4 different depths: 0.25, 0.5, 1.0 and 2.0 m from the upper surface. Two piles of 0-90 and 20-90 mm were sheltered from rain during the research as to find out if it would affect the carbonation. In a non-sifted conventional pile of 0-90 mm CO_2 concentrations varied from 20-130 ppm. The lowest concentrations were seen at the bottom of the pile at 20 ppm and 130 ppm at the surface layer. It was observed that carbonation occurred at the bottom of the pile, although at a slower rate and after after 6 months 85% of concrete 0-90 was carbonated which corresponds with the same DoC as displayed in SIS, 2019 for concrete surfaces exposed to rain. Additionally, the tests conducted in Finland, no substantial difference in the piles that were sheltered from rain could be observed as they dried out quickly.

Another study of CO_2 sequestration in various fractions were presented in (SIS (2019)) and it was observed that smaller fractions carbonated at a faster pace, more specifically 0-4 mm. One cubic metre of concrete with a cement paste of 350 kg/m^3, with an assumed water-cement ratio of 0.43, was crushed into three fractions with a depth of 0.4 m and placed in pallets sheltered from rain: 0-4, 4-8 and 4-16 mm. The three fractions generated a total uptake of 37 kg CO_2/m^3, about 8.3 kg / ton concrete after 18 months of storage. These results were similar when compared to two other studies in SIS (2019). In comparison with mixed stockpiling, this approach generated a 4 time higher carbon sequestration. It is essential to sort the piles into similar fractions to create void space to allow airflow for a more efficient carbonation. According to the study by Leemann et al. (2023), it was concluded that finer particle sizes allow for a more efficient carbonation, with 0-4 mm achieving the best uptake of CO_2. Interestingly, fractions of 4 mm of high-quality concrete didn't carbonate at all. Furthermore, in their findings, 80 % of the carbonated cement paste had carbonated after 1.5 months of their total 6-8 months of storage. Similar to results from Skanska Finland and Toni Kekkonen Betoni, 2023, it was observed that the DoC was only marginally higher at the outer layer of the studied stockpiles, and still carbonated at a similar degree at a depth of 1-2.5 m.

Initially, a DoC is needed in order to estimate storage time, where after that time period the CA can be tested by thermogravimetric analysis (TGA) which measures weight loss between temperatures 500 - 1000 degrees celsius to calculate captured CO_2.

Carbonation occurs rapidly after demolition concrete has been crushed when a new fresh surface comes into contact with the air. It is necessary to determine a degree of carbonation in order to calculate the amount of captured CO_2. Since this process slows down over time, there is thus an optimal storage period.

2.4.2 Accelerated carbonation

This chapter will introduce two methodologies possible for accelerating the sequestration, both of which are mainly theoretical and not as of yet applied in a larger scale. This will however serve as a foundation for exploring potential future management plans for CA by examining the literature on carbonation and combining it

with the case study of the MPPs.

Carbonation of concrete is desirable for the construction sector as it reduces the carbon footprint, which consequently have increased studies on the subject along with accelerated carbonation technologies. The amount of accelerated carbonation technologies that have been tested on an industrial-scale are rather limited, and so most are under development in laboratory settings and falls roughly into two methods; Applying pressurized CO_2 in a chamber or adding a solvent in which the sequestration takes place (Li and Wu, 2022). By applying an accelerated carbonation technology on concrete aggregates (CA) one can achieve the following:

1. Speeding up the CO_2 sequestration process.
2. An increase in uptake efficiency compared to letting the concrete carbonate naturally, effectively increasing the DOC.

2.4.2.1 Fastcarb: a case study in France

In France, an initiative aimed at studying the feasibility in accelerated carbon capture via RCA. Two pilot installations within cement plants utilized untreated industrial gases emitted from cement kilns and processed quantities on an industrial scale. The crushed aggregates (CA) used were in the fractions 0-4 mm and 4-16 mm Torrenti et al. (2022).

The first installation was a rotating drum of 11 m in length and with a radius of 2m, where the RCA was placed for carbonation with a connected pipe with flue gases emitted from a cement kiln. The temperature of the gas was 60-80 degrees celsius with a CO_2 concentration of 11-16 % and a relative humidity (RH) in the drum of 90 %. With a capacity of 3 tonnes of RCA it showcased an optimal residence time of 1h, which in the end resulted in 2h when including filling and emptying of the drum. The rotating drum resulted in an average carbon capture of 31 kg CO_2/ton for the fractions 0-4 mm and 5kg / t for 4-16 mm.

Another installation was made which utilized a fluidized bed which resulted in slightly higher carbon uptake at 39 kg CO2 / t for the fraction 0-4 mm and 12 kg CO2 / t for 4-16. The flue gas in this case had a CO_2 concentration of 20%. Overall, the Fastcarb project showcased that the fraction 0-4 mm was of most interest in a carbonation perspective and could capture 25-40 kg CO_2 per tonne, results that were similar to tests under in laboratory settings. Industrial flue gases constitute of several substances apart from CO_2 such as NOx and SO2 and was observed to adversely affect carbonation Torrenti et al. (2022) when compared to a stream of air without NOx and SO2. Furthermore, In the summary of the Fastcarb project, it was evident that emissions and the gains of carbon sequestration were largely affected by the transportation of aggregates. Bergmaterialindustrin (2019) argues that Exceeding a transportation distance of 20 km with aggregates is not deemed reasonable in an economical nor environmental perspective.

As previous research has concluded, particle size matters, and finer fractions increases the surface area of concrete that can be carbonated SIS (2019), Stripple et al. (2018), Torrenti et al. (2022). In addition to this, a RH of 40-80 % was deemed optimal for carbonation as too little moisture wouldn't enable the carbonation process and too much would slow down the diffusion of CO_2 into the cement pores. In Li and Wu, 2022 it was however argued that a higher water content with elevated temperatures may boost carbonation as it promotes two important aspects for the process: Diffusion of CO_2 and leaching of calcium ions. The solubility of those two is however reduced, which is why an addition of water is needed.

Li and Wu (2022) further explains that a significant acceleration of the carbonation occurred when increasing the CO_2 concentrations from atmospheric levels (0.03 %) to 20-40 %. A continuous increase of concentration from 40-100 % showed marginal improvements on the carbonation. The study concluded that surface area (particle size) of the aggregates and temperature were deciding factors in carbonation efficiency. The process could be sped up by increasing pressure and CO_2 concentrations, these factors did not however prove to increase the overall degree of carbonation.

Increasing temperatures accelerate the diffusion of CO_2 and speed up carbonation reactions, which boosts the capacity for CO_2 absorption and reaction rates. However, elevated temperatures also promote the formation of calcite layers and particles, as depicted in Figure 5. These calcite layers adhering to mineral surfaces may hinder the release of calcium ions, while calcite particles can densify the porous structures of cement paste, thereby slowing down the diffusion and dissolution of CO_2 [102]. Consequently, the influence of rising temperatures on the carbonation process of materials entails two conflicting factors.

3
Method
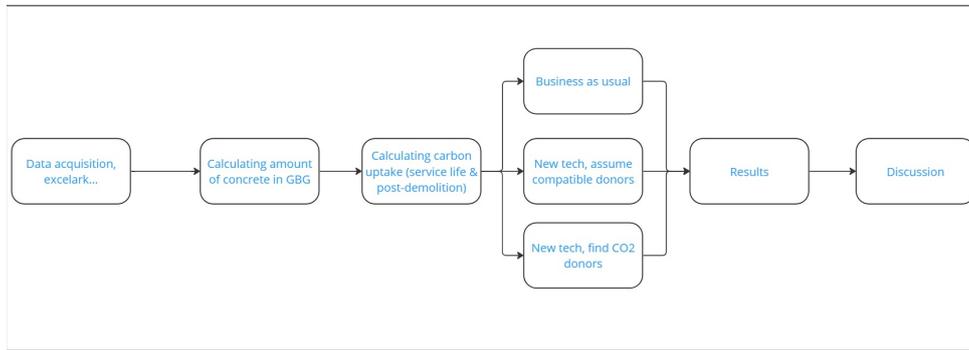
Figure 4: Overview of steps in methodology

The methodology comprises data acquisition related to the physiology of cement, concrete, and carbonation through a literature review, the

3.1 The case study: the million program 1965-1974

The case study aims to quantify the carbon capture potential in the concrete stock in million program (MP) buildings built between 1965-1974, in the municipality of Gothenburg. 1.4 million homes were built in Sweden between 1961-1975, of which a million were built between 1965-1974 in what became known as the *million program.* The million program was a response to housing shortages and poor living conditions in Sweden during a period of rapid economic growth and labor migration after the Second World War. Employment opportunities and vacancies in urban areas led to an influx of citizens from the hinterlands during the 1950s and 1960s (Molinder, 2018). Sweden's three largest cities; Gothenburg, Malmö, and Stockholm; together had 330'000 new multi-family housing built during the million program (Johansson, 2012), an indicator of the influx of citizens to urban areas that Sweden experienced during this time. Today, buildings constructed during these years make up approximately 30% of all homes in Sweden according to data from Statistics Sweden (2023). These buildings are approaching their technical lifespan, and are in need of reconditioning, as shown in figure 5. Research by Thuvander et al. (2015) indicates that only a third of the buildings from this era had been refurbished by 2015. A report by the Swedish construction firm NCC (2021) estimates the total cost of renovating these buildings at 500 billion SEK, the equivalent of about 10%

of Sweden's GDP in 2021 (Our World In Data, 2022). Of all homes constructed during the million program, ca. 75'000 were built in the municipality of Gothenburg, which today amount to ca. a third of its housing stock (Göteborgs Statistikdatabas, 2022). The plan of erecting one million homes in one decade necessitated industrialized construction techniques with many prefabricated components. The implementation of these innovative building practices intended to ensure affordability, with the goal that a two-room apartment should cost no more than a fifth of an industrial worker's salary, which became possible with these new building practices, as well as through beneficial government loans (SCB, 2024; Sveriges Allmännytta, n.d.). Reinforced concrete was the preferred material to construct MP buildings

Figure 5: Number of million program apartments in need of renovation per region in Sweden (NCC, 2021).

(Björk et al., 2016). It was cost-efficient, robust, and low-maintenance, all attractive characteristics for constructing functional, multi-story apartment buildings. During the height of the MP the domestic use of concrete reached levels that have not been seen since, see figure 6. This extensive use comes with environmental drawbacks related to its production, but there are also issues with end-of-life waste management of concrete, which will be important to address in the future when this large building stock reaches its technical lifespan.

The MP was successful in that it mitigated the housing crisis and provided cheap apartments, but it was already criticized from the beginning for its architectural uniformity, lack of green areas, and concerns about social issues that arise from locating large groups of low-income citizens within specific geographical areas (Boverket, 2020; Lundberg, 2018). With these buildings reaching the end of their technical lifespan in the coming 40-60 years, there is an active public debate on the future of the million program, with stakeholders voicing a number of concerns. Segregation, energy efficiency of buildings, the growing number of dwellings in need of renovation, as well as the costs related to this, are all points raised in the last 15 years (Johansson, 2012; Mossfeldt, 2011; NCC, 2021; Nytt & Viktigt, 2014; Vicktor, 2009).

Figure 6: Amount of cement and concrete used in Sweden 1893-2011 (Andersson et al., 2013)[1].

3.1.1 The future of the million program

The million program is, as explained by Johansson (2012), a polarizing subject in Sweden. The subject of an urgent need of refurbishment and the importance of addressing social issues linked to MP areas are brought up in public debates. For the sake of the problem formulation of this thesis it will be assumed that all buildings are demolished after a service life of 100 years, arguments for this assumption are presented in 3.2.

3.2 Effluence of concrete from MP building stock

The temporal material flow rate in the end-of-life phase of buildings is poorly understood and is the focus of ongoing research. The useful life of a building is difficult to assess with certainty due to the many involved variables that lead to the demolition of a building. Previous research on this topic has used various types of probability distributions to predict future demolition rates, but Miatto et al. (2017) acknowledges that there is no agreed upon model that estimates the amount of accumulated construction material at urban or national levels. The choice of probability distribution depends on demolition patterns, the nature of the built environment, and on the availability of data, none of which currently is available at any reliable rate for Sweden Tiberg, 2024. Predicting the lifetime of buildings in Sweden using previous research is further complicated by the fact that they have mainly been carried out in Asia, where the average lifespan of buildings can be as short as 30 years, which does not reflect the situation in Europe, where more than 40% of the building stock in 2011 was constructed before the 1960s (Andersen and Negendahl, 2023; Daigo et al., 2017; Economidou, 2011; Ji et al., 2021; Liu et al., 2014; Miatto et al., 2017).

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[1]Reprinted with permission. ©2024 American Chemical Society

Wiedenhofer et al. (2015) have modeled the flow of material stock in the EU25 and found that Sweden has one of the lowest annual mean demolition rates with 0.03% for the years 2003-2009. This demolition rate is based on a collection of the most common residential buildings in the EU in 2003, which the authors acknowledge only represent 80% of the building stock leaving a considerable uncertainty. The low demolition rate points to the fact that buildings have a longer life in Sweden, compared to other nations. Data from Göteborgs Statistikdatabas (2022) shows that the total building stock from 1961-1980 in Gothenburg grew ca. 1% between 2014-2022. According to email correspondence with Göteborgs Stad this is due to variations in the building stock due to reconstructions and corrections of error of reporting from property owners.

Johansson (2012) argues that the million program, in comparison to other large-scale housing programs in Europe during the same era, was well built and meant for a growing middle class and that it will surely last 100 years. In 1994 new regulations for the lifetime classification of concrete structures were introduced, with the L2 class assuring a lifetime of 100 years, and L1 class 50 years. With the MP being constructed before these regulations were implemented, it can still be assumed that they were built with such robustness that a lifetime of 100 years can be assumed. Multiple studies investigating carbonation uses 100 years as the assumed time horizon for the service life of concrete buildings for calculation purposes (Andersson et al. (2013) and SIS (2019). This will mean that a 100 year lifetime for the MP will be fulfilled in 2065 for the buildings constructed in 1965 and so on, see figure 7 for concrete output per demolition year.

3.3 Calculating the concrete stock and use-phase CO_2 sequestration in the million program in the municpality of Gothenburg

To properly assess the carbonation potential in the concrete stock from the case study, a first step is to analyze how large the concrete stock is, and how much carbon has been bound in the buildings during their assumed lifetime of 100 years. This will showcase the degree of carbonation and how much of the concrete that remains available for CO_2 sequestration. The data of the concrete stock was obtained from a provided excel file (Adamu and Bhattarai, 2022), which had data on the quantity of concrete in buildings constructed in the municipality of Gothenburg. These values were divided into groups per construction year and summarised, to get a picture of how much concrete waste could be generated under the hypothetical scenario that the technical lifetime of a building is 100 years and that it is immediately demolished once it reaches its assumed lifetime. The data in the Excel document was based upon the analysis of 46 typical residential buildings in Sweden constructed over the time frame 1880-2010, comprising 12 single-family and 36 multi-family type buildings. In the context of this thesis, only the multi-family buildings are to be studied. The report from which the Excel file is derived used material intensity data to calculate the concrete stock in Gothenburg.

The Excel file also provided coordinates for each building which was inserted into the geographical information system software *QGIS* to visualize the geographical location of the concrete stock to investigate transportation emissions, see figure 10. To understand the spatial spread of buildings per construction year each building was assigned a specific colour, as seen in figure 10.
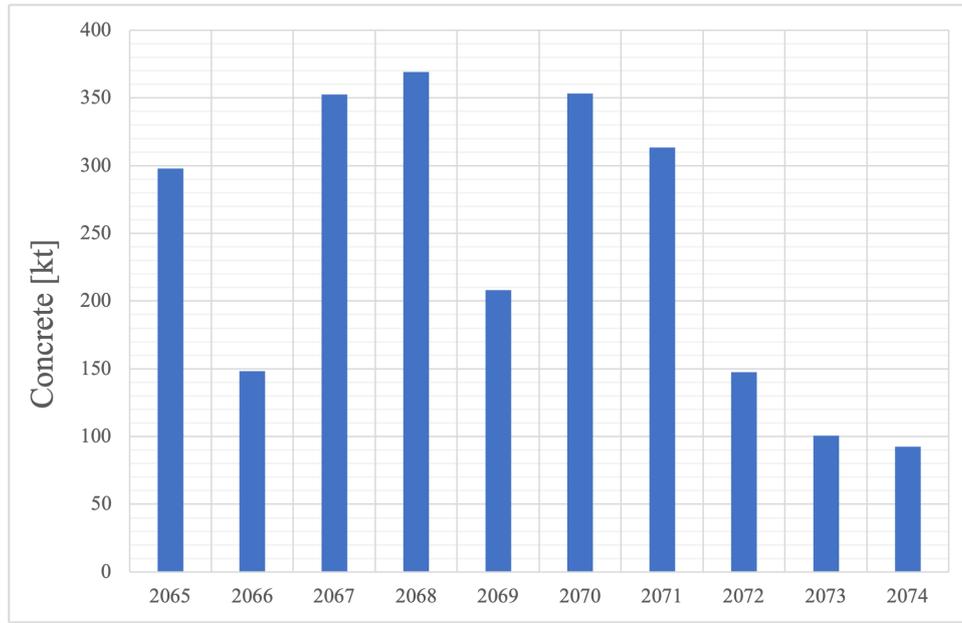
Figure 7: Effluence of concrete from the MP building stock in kilotonnes, per assumed year of demolition.

3.3.1 CO$_2$ sequestration use-phase

To properly assess the carbon uptake of a building during its service life, it is important to obtain as much data as possible on the buildings. Surface areas, wall coatings, indoor and outdoor environment are all factors determining how much carbon is captured during a buildings service life (Munthe, 2013; SIS, 2019; Stripple et al., 2018). Many parameters beyond the exposure levels also contribute to the actual carbonation depth of a concrete element during its technical lifespan, such as the compressive strength of the concrete and the clinker ratio. SIS (2019) calculated a mean use-phase carbonation value of a concrete multi-family residential building to be 20 kg CO$_2/m^3$. This value is for an assumed technical lifetime of 100 years, a cement with clinker ratio of 95%, a cement ratio of 330 kg cement/m^3 of concrete, and a compressive strength of 25 MPa. These values are representative for a MP building, as explained by Andersson et al. (2013), and as well as by construction documents of an MP building from 1967 obtained from the Gothenburg city planning office.

To calculate the amount of sequestrated CO$_2$ during the technical lifespan the equation 3 is used:

(3) $$C_a = \beta V$$

where C is the total amount of sequestrated CO_2 in kg, β is the mean amount of CO_2 in kilograms that is sequestrated per m^3 of concrete during 100 years, and V is the total amount of concrete in m^3. To calculate the carbonation degree, equation 4 is used:

(4) $$C_d = \frac{\beta}{eC_c}$$

where C_d is the carbonation degree in %, e is the ratio of emitted CO_2 from calcination in kg to the production of 1 kg of cement, and C_c is the ratio of cement to m^3 of concrete.

3.3.2 Transport distances

Using the software QGIS enables measurement of the mean average linear distance between emitter and resource parks. In QGIS the coordinates for the resource parks were identified through the use of pythagoras equation the shortest linear distance between all MP buildings and the resource parks was calculated. The same method was used to find the shortest distance between the resource parks and CO_2-donors to highlight the shortest routes of transportation from processing sites to emitters to apply an industrial symbiosis and to keep the transportation distances as short as possible.

3.3.3 Resource parks

An initial step was to identify where the eventual masses of demolished concrete will be transported and processed. Information about the location of potential resource parks were acquired by research and discussions with Skanska. These were then plotted on a map in QGIS and mean transportation distances were determined by adding an 8.7 km radius around each processing site in QGIS as shown in 12. The radius was chosen to avoid an overlapping. This appliance will illustrate the areas of buildings that are closest in a linear distance to the processing sites. Buildings outside of the circles or in-between are measured in a linear distance in QGIS to sort them to the closest processing sites. Once distances are established, the transportation emissions can be calculated accordingly by multiplying an emission-transportation factor presented in table 3.

3.3.4 Natural carbonation

The following parameters as presented in 3 are used to calculate potential CO_2 sequestration and time frames for the respective scenarios. As the concrete elements are crushed into various fractions, the volume subsequently increases and is assumed

Table 1: Carbonation parameters from literature.

Carbonation method	Fractions [mm]	CEM-type	Degree of carbonation [%]	Residency time	Study
Natural carbonation	0/90	n.m	85	6 months	[2023]
Natural carbonation	0/4,4/8 & 8/16	I	34.4	18 months	[2019]
Fastcarb	0/4	I,II,III	37-59	60 min	[2022]
Fastcarb	4/16	I,II,III	18	60 min	[2022]

to be similar to that of virgin aggregates of similar fractions i.e. 1.6 t/ m3 which results in 220 kg cement / m3 concrete.

The method of storing 0-90 mm in piles of 2 meters in height which, according to Co2ncrete Solution (n.d.), would result in 85% carbonation after a period of 6 months was one of the few studies which analyzed larger stockpiles of concrete closer to the operational realities of aggregate production. Each resource park will have a varying maximum capacity of storing concrete depending on which pile dimension Results provided in a study conducted in SIS (2019) presented a total of 37 kg of CO_2 / m3 after 18 months by piling in 3 separate fractions of: 0-4, 4-8 and 8-16 mm. For this thesis, the piles were stored in 0.4 m and on pallets. Utilizing the parameters from both studies, the outcomes in this study will provide a range of potential CO_2 sequestration estimates, spanning from a minimum to a maximum value.

As described by Munthe (2013), the current waste handling system in Sweden results in an intermediate stockpiling of demolished concrete for 0.5-4 years and 1-4 months for the storage of mixed fractions. If approximately 6 months are needed for intermediate stockpiling and crushing of demolished concrete, and if the intermediate stockpiling of mixed fractions (0-90 mm) also takes 6 months to achieve 85% carbonation, the total processing time for CA would be 12 months. It is assumed that the storage space for an inflow of concrete prior to processing is not an issue. This time frame of 12 months will be used in the calculation examples when investigating the 2m scenario.

Time frame: 2 m scenario
- 6 months initial processing & intermediate storage
- 6 months carbonation to achieve 85% DoC
- Tot. processing time: 12 months

Time frame: 0.4 m scenario
- 6 months initial processing & intermediate storage
- 18 months carbonation to achieve 34.4% DoC
- Tot. processing time: 24 months

An overview of the processes is presented in figure 11 and includes the demolition process from which the concrete is crushed into transportable pieces, use of load-

Conrete buildings

Demolition

Loaders

Transportat
ion

Loaders

Fuel →

Crushing

→ **CO2**

← **CO2**

Loaders → Transpor
tation

Loaders

Natural
carbonation   Accelerated
carbonation
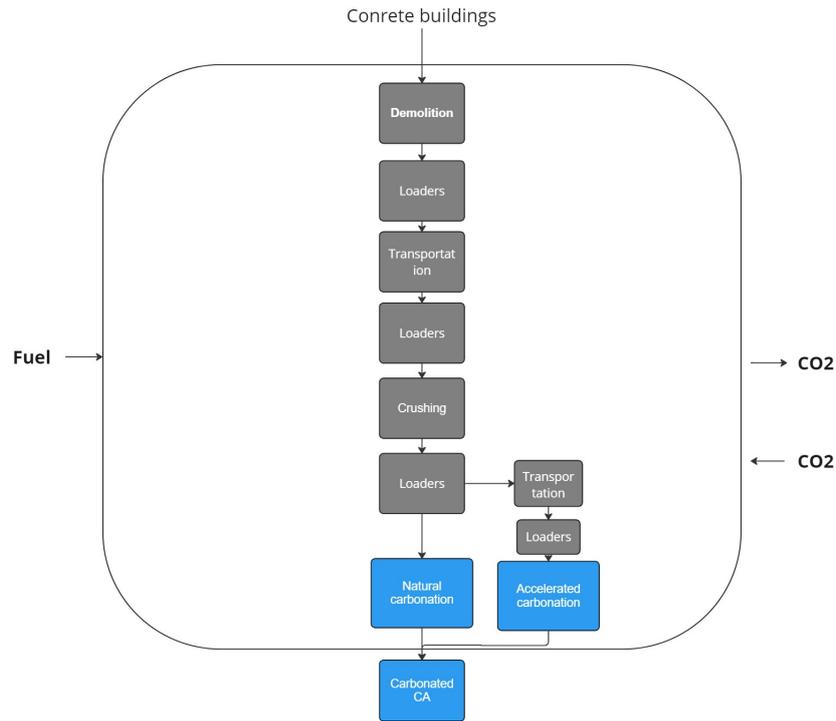
Carbonated
CA

Figure 8: Overview of required steps for utilizing concrete in natural & accelerated carbonation

ers for loading and unloading crushed concrete onto trucks and into stockpiles, and transportation for further processing at the resource parks where its crushed into the desired fractions of either 0/90 or 0/4,4/8 and 8/16.

3.3.5 Cone-geometry and resource park processing capacity

By using the provided height from the studies of Stripple et al. (2018) (0.4 m height) and Skanska Finland and Toni Kekkonen Betoni (2023) (2 m height) along with standard practices of storing cone-shaped or rectangular-shaped piles, a first observation of required space for the concrete aggregates can be made. For each of the two cases the volume of a conical stockpile with an assumed 37° angle of repose, which is a common value for stockpiling concrete as per Concrete Plants Inc. (n.d.), can be calculated by equation 5:

$$(5) \qquad\qquad V_c = 1.836h^3$$

where V_c is the volume of a cone and h is the height of a cone in meters.

To calculate the maximum amount of concrete that can be stored at the three identified resource parks Vikan, Kållered, and Gunnilse the approximate size of each site, hereafter notated A_{rp}, was measured with the area measuring tool in QGIS. To

calculate the maximum amount of concrete that can be processed with respect to the size of the resource parks the radius of a cone is calculated with equation 6:

$$(6) \qquad r = \sqrt{\frac{3V_c}{\pi h}}$$

The floor area, A, of a cone is then calculated with equation 7:

$$(7) \qquad A_c = \pi r^2$$

To calculate the maximum volume of concrete that can be processed at each resource park, V_{rp}, equation 8 is used:

$$(8) \qquad V_{rp} = \frac{A_{rp}}{A_c} V_c$$

3.3.6 Accelerated carbonation

As a Fastcarb unit requires a steady inflow of CO_2, the initial step involves identifying industrial sites within reasonable proximity that emit CO_2 in order to investigate a potential industrial symbiosis. As previously mentioned in 2.4.2 a transportation distance exceeding 20 km for aggregates surpasses the threshold where costs and emissions become too high (Bergmaterialindustrin (2019)). It is assumed that *one* Fastcarb unit is attached to the chosen industries outflow of flue gases where the performance is equal to that of the pilot installation in the case study of Torrenti et al. (2022). The steps involved for accelerated carbonation are represented in 8

Observing the distances and analyzing maps provided by The European Pollutant Release and Transfer Register (E-PRTR) facilitates the identification of potential sites to implement an industrial symbiosis with the industries as CO_2 donors for the Fastcarb unit, see figure 9 for selected CO_2 donors. The seven sites that have been included as CO_2 donors in this thesis are selected upon their emissions of CO_2, the other sites within the municipality of Gothenburg did not have data for CO_2 emissions.

Table 2: Parameters affecting the carbon uptake for Fastcarb. Ranging from an uptake of 25-40 kg CO_2 / t concrete.

Processing time [h]	Concrete processed [t/yr]	Min. sequestration potential [t]	Max. sequestration potential [t]
2 024	3 036	75.9	121.44

Similar to the stockpiling scenarios, the time frame for processing CA in the Fastcarb scenario is presented as follows:

Figure 9: Sources of industrial CO_2 emissions in the municipality of Gothenburg (European Environment Agency, 2024)

- 6 months initial processing & intermediate storage
- 12 months carbonation to achieve 37-59% DoC

3.3.7 Emission factors

In an attempt to quantify the net-gains of carbon sequestration in the different scenarios, various emission posts connected to leveraging concrete as a carbon sink have been identified. Among the processes are demolition, transport, loaders, crushing and emissions connected to operating a Fastcarb unit, referred to as carbonation infrastructure in table 3.

The emission factors are presented in table 3. Emissions from the procedure of producing CA in different fractions varies depending on how many crushing steps are necessary. 0/90 requires 2 crushing steps and for 0/4, 4/8 and 8/16 3 crushing steps are required. The crushing emissions is a mean value calculated from 4 different resource parks in the region of Västra Götaland deriving from information supplied by Skanska. The emissions will be allocated to the amount of processed concrete in each scenario. This is to make the potential CO_2 sequestration for the actual processed concrete comparable to the emissions for this same amount of concrete. In other words: emissions from excess concrete that can't be processed due to capacity limitations wont be accounted for in the net emissions. The total emissions for

each scenario are subtracted from the sequestrated CO_2 to present the net carbon capture.

Table 3: Emissions from EoL processing of concrete

Process	Emissions	Study
Demolition	**0.007** [kg CO_2 / kg concrete]	2021
Transportation	**0.106** [kg CO_2 / tkm]	2019
Crushing	**1.63-1.92** [kg CO_2 / t concrete]	2024
Carbonation	**1.3** [kg CO_2 / t concrete]	2023
Loader	**1.18** [kg CO_2 / t concrete]	2024

3.4 Limitations

3.4.1 Scope and scale

The thesis is confined to evaluating the CO_2 sequestration and emissions connected to the cement bound in the MP buildings constructed 1965-1974 in the municipality of Gothenburg. The time frame of the thesis is firstly based on the assumption of a 100 year service life for each of the MP buildings. After demolition, there are three different scenarios of carbonation occurring which will process the CA in three separate time frames. As it is difficult to know what the future holds in terms of energy mixes, fuel use, processing equipments, and demolition practices the emission coefficients and scenarios are based on a business as usual scenario.

3.4.2 Theoretical limitations

As there is no standardised method of measuring the uptake of CO_2 in CA it results in studies presenting sometimes contradictory data that the scenarios in the thesis are based upon. Moreover, there is a lack of studies investigating the industrial scale of carbonation in stockpiles. Flue gases have various compositions depending on the industry. The calculations in this thesis are based on flue gases being similar to that of the cement kiln in the pilot installation in France, and that the fastcarb machine can capture 25-40 kg when paired with flue gases from the chosen industries in VGR. This thesis does not account for economic aspects of constructing this carbonation system.

3.4.3 Technical limitations

A mean average linear distance is applied to get an overview of distances and subsequently emissions connected to transportation of demolished concrete. Future research directions are recommended to delve deeper into demolition of buildings, as there is very limited data on predicting the demolition rates which is the foundation for the material flow rate and thus the on potential sequestration in concrete processed at the EoL. The calculations presented in 2.2.2 are explained as a background for carbonation calculations, but this method is not viable for use in this thesis due to time constraints and the sheer volume of buildings examined. Instead in-situ carbonation values are used.

4

Results & discussion

The following section presents the results and discussion for the location, the amount of concrete bound in, and the assumed year of demolition for the MP buildings of interest to this thesis: multi-family concrete buildings constructed in Gothenburg municipality between 1965-1974. The CO_2 sequestrated during the MP buildings lifetime is also presented as well as the potential for CO_2 sequestration after the demolition of the buildings in three different scenarios: stockpiling in 0.4 m or 2 m and using Fastcarb technology.

4.1 Location and concrete stock in the case study

The data in the provided excel-file resulted in 1 142 buildings being identified after removing buildings which lacked coordinate data or were located in the archipelago, which is presented in figure 10. Table 4 presents the amount of concrete bound in the MP buildings aggregated per year of construction. For Gothenburg municipality it can be seen that the largest amount of concrete is found in buildings built year 1965 and 1967-1971, with a steep drop-off for 1972-1974 and with 1966 having quite low volume as well. This can be interpreted as the mid 60s to early 70s being the peak years for the completion of MP buildings in Gothenburg municipality. As for the location of the buildings, figure 10 shows that the location of the buildings are in large south-west to north-east in relation to Gothenburg city-center. Each dot represent a building, and they are color coded by construction year. It can be seen that for the early years, 1965-1970, the buildings are located in the south-west and north-west, while buildings constructed later have more central or northly locations.

4.2 Lifespan and CO_2 sequestration during use-phase

Table 4 presents the results for the amount of sequestrated CO_2 during the lifetime of MP buildings constructed in the years 1965-1974. A total of 19 857 tons of carbon dioxide can be bound in the concrete of the 1 142 buildings during an assumed lifetime of 100 years, see 3.2 for arguments for assumed lifespan. This amounts to a lifetime DoC of 12.4 %, which agrees well with established use-phase carbonation degrees of 10-20 % in the aggregated data from SIS, 2019. It should be emphasized that the used carbonation value to retrieve this result of 20 kg CO_2/m^3 derives from
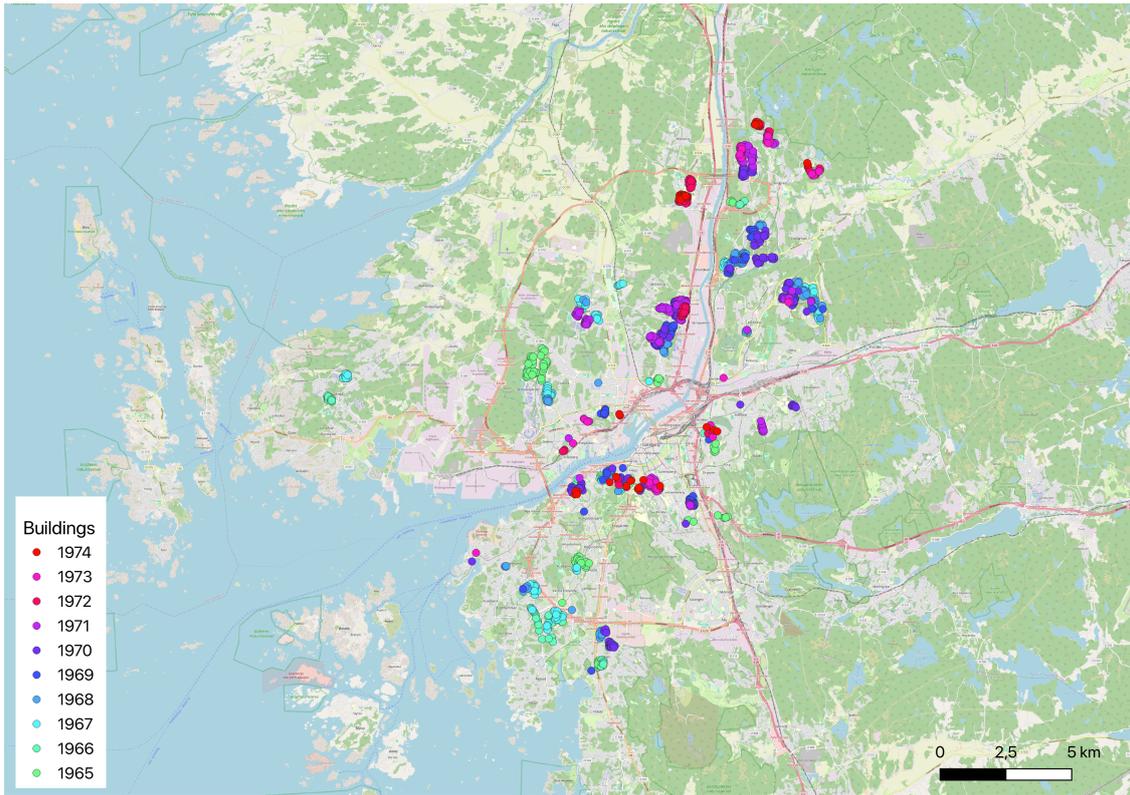
Figure 10: Location of MP buildings in Gothenburg municipality, colour sorted by construction year. Picture captured from QGIS.

Table 4: Amount of concrete in the MP buildings per year of construction, the amount of sequestrated CO_2 during their assumed lifetime of 100 years and the degree of carbonation.

Construction year	Amount of concrete [t]	CO_2 sequestration use-phase [t]	DoC [%]
1965	297 708	2 481	12.4
1966	148 127	1 234	12.4
1967	352 344	2 936	12.4
1968	369 298	3 077	12.4
1969	208 169	1 735	12.4
1970	353 272	2 945	12.4
1971	313 253	2 610	12.4
1972	147 607	1 231	12.4
1973	100 717	839	12.4
1974	92 315	769	12.4
TOT	**2 382 810**	**19 857**	**12.4**

a case study on a singular building to capture data on exposure conditions of all concrete elements in great detail. This method would however be excessively time-

consuming to conduct for the number of buildings examined in this study. This result implies that 12.4% of the reactive CaO in the cement has reacted with atmospheric CO_2 during the use-phase to form chemically stable $CaCO_3$, subsequently scaling down the remaining amount of CaO available for carbonation. This highlights the potential of carbonation in the EoL, as there is a remaining 87.6% CaO available for carbonation, which provides valuable insight into the environmental performance of concrete buildings during their EoL-stages.

4.3 Resource parks

Three resource parks were identified in the scope of this report: Vikan, Kållered and Gunnilse. Their respective geographical contexts are presented in 11. Vikan resource park is an approximately 40-hectare large area and is today used for quarrying stone. It is located on Hisingen island approximately 7 km to the west of Gothenburg city center. Kållered is an approximately 42-hectare large quarry that is located approximately 13 km to the south of Gothenburg city center, and Gunnilse is, as of this reports completion, a resource park that is not yet in use. Gunnilse is a 5-hectare area which is located 11 km to the northeast of Gothenburg city center. For calculation and logistical purposes, within the scope of this report, these three resource parks will solely be used for retrieving and storing crushed concrete in three different scenarios:

- Crushing and storing concrete in cone-shaped stockpiles with a height of 2 meters for a DoC of 85%

- Crushing and storing concrete in cone-shaped stockpiles with a height 0.4 meters with a DoC of 34.3 %

- Crushing concrete for utilization in Fastcarb units at identified CO_2 donors

Figure 11 illustrates the geographical context of the resource parks with a radius of 8.7 km drawn around each site. Figure 12 shows the annual inflow of concrete from MP buildings prone to demolition, based on the shortest mean average linear distance to each resource park. Figure 12 together with figure 11 explains the difference in the amount of concrete transported to each site. The method used in this report aimed at keeping the transport distance of the concrete from each demolished building to each resource park as short as possible to avoid excess transport emissions. With Vikan and Gunnilse being more centrally located in Gothenburg, and therefore in a closer proximity to the MP buildings as visualized in figure 11, they will receive more concrete than Kållered resource park which is located in the far south. It is noteworthy to mention that due to this choice of method, Kållered resource park will not recieve any concrete in 2067 and 2071-2074 as Vikan and Gunnilse are closer to the buildings that are demolished these years.
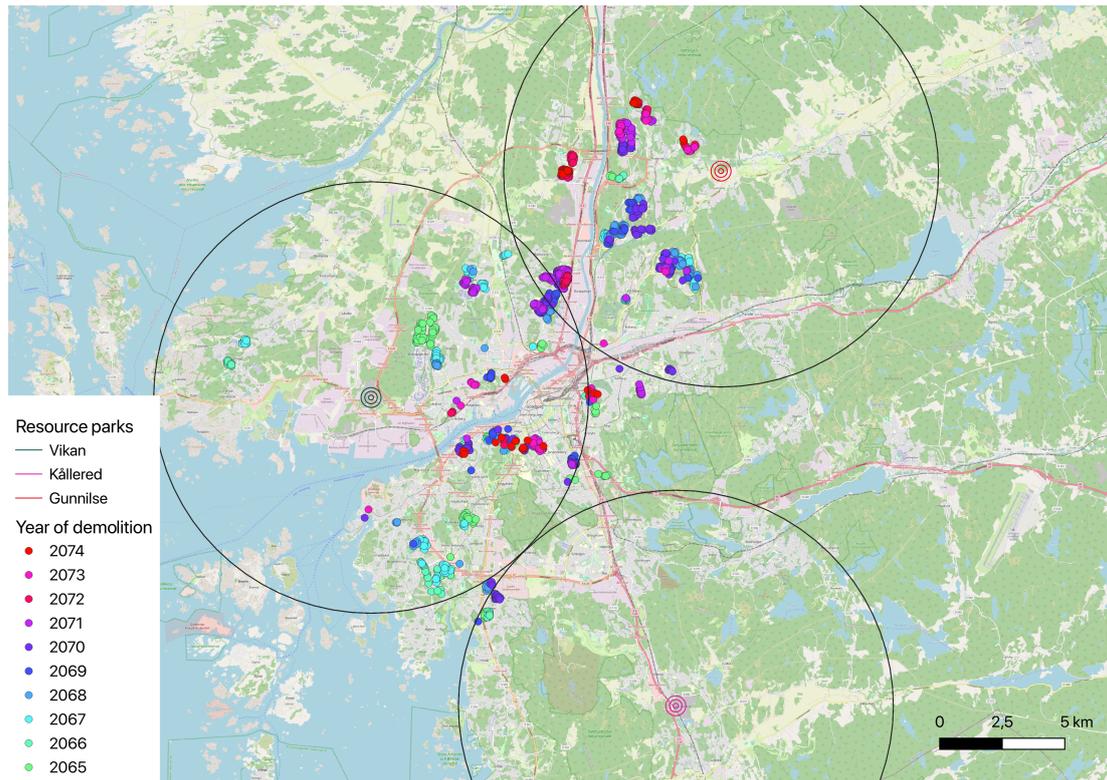
Figure 11: Circles with a radius of 8.7 km have been drawn around each processing site to visualize the shortest transportation route. Picture captured from QGIS.
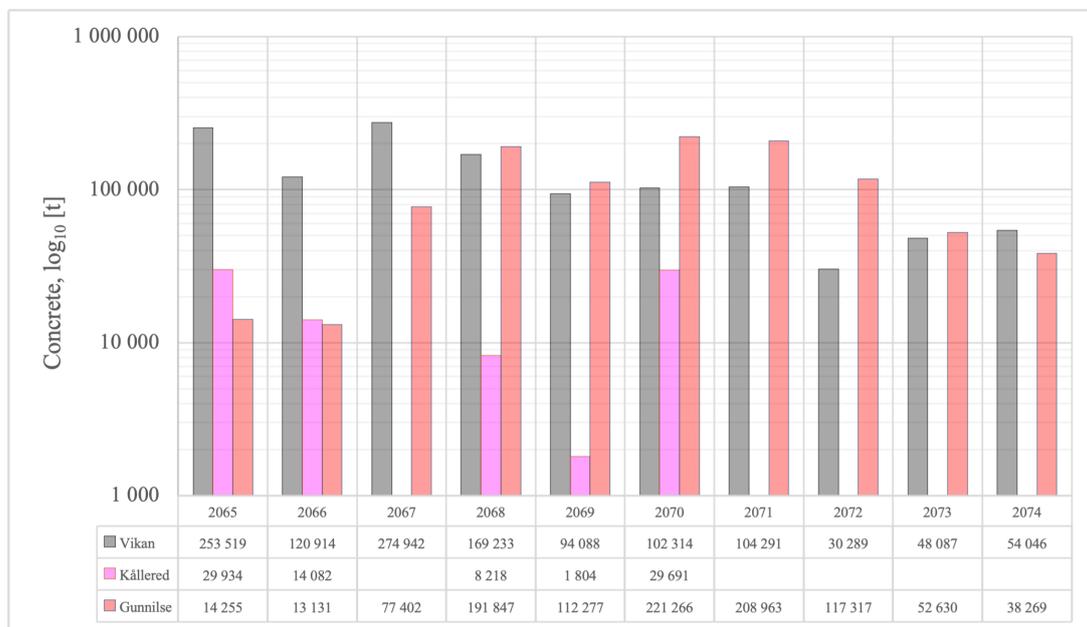
Figure 12: Amount of concrete that is transported to each of the three resource parks annually.

4.4 Natural carbonation

Natural carbonation will occur in two separate scenarios:

- 1. Stockpiled in 2 meter height with 85% DoC (Skanska Finland and Toni Kekkonen Betoni, 2023)

- 2. Stockpiled in 0.4 meter height with 34.3 % DoC (Stripple et al., 2018)

The following sections will present the results for how much of the inflow of concrete to each site that is able to be processed in relation to the capacity for each of the two scenarios. In some cases, there will be enough space for stockpiling all concrete that is sent to the resource park, resulting in a surplus volume available for processing and in some cases, reversely, there won't be enough space to process the inflow and will thus result in concrete not being able to be processed at the site.

4.4.1 Pile geometry

Table 5 and table 6 presents the parameters for determining the total volume of concrete that can be stockpiled at each resource park, for the 0.4 m case and the 2 m case respectively. Table 7 shows the results for the processing capacity of each resource site in m^3.

Table 5: Cone geometry data for a pile of 0.4 m in height

Radius [m]	Volume [m^3]	Height [m]	Floor area [m^2]
0.53	0.118	0.4	0.881

Table 6: Cone geometry data for a pile of 2 m in height

Radius [m]	Volume [m^3]	Height [m]	Floor area [m^2]
2.648	14.688	2	22.033

Table 7: Processing capacity of the resource parks.

Resource park	Processing capacity 0.4 m scenario [m^3]	Processing capacity 2 m scenario [m^3]
Vikan	53 333	266 667
Kållered	56 000	280 000
Gunnilse	6 667	33 333

4.4.2 Vikan resource park

The results for the amount of concrete that can be processed by Vikan in the 0.4m stockpiling scenario is presented in table 8. While the maximum processing capacity of crushed concrete for this scenario at Vikan resource park is 53 333 m^3, the amount of concrete that is transported to the site exceeds this limit 2065-2071. In table 8, column four, the amount of concrete that is not processed these years are shown. The amount of concrete that can not be processed varies between 5 472 tons (2069) up to 118 504 tons (2067), a consequence of the varying amounts of concrete that is transported to the site each year. For all ten years Vikan can process 58.2 % of all concrete that is transported to this site.

In table 9, the scenario of 2 m stockpiling provides a capacity of processing 266 667 m^3 of concrete. As the inflow doesn't exceed the capacity during any of the years 2065-2074 meaning 100% of the inflow of concrete can be processed. Subsequently, there will be a surplus volume available these years that can be used to process concrete from other resource parks. For the period spanning 2072-2074 the storage capacity is projected to be adequate. This is attributed to the diminished inflow of concrete, which is a consequence of the lower number of buildings constructed during the years 1972-1974. Figure 13 illustrates the total inflow of concrete to Vikan resource park annually with the horizontal lines displaying the max capacity for each stockpiling scenario, visualizing the large available volume for the 2 m scenario in comparison to the 0.4 m scenario.

Table 8: Total inflow of concrete to Vikan annually and the share that can effectively be processed due to area restrictions for the 0.4 m scenario.

Resource park: Vikan Approx. size: 40 ha Processing capacity, 0,4 m scenario: 53 333 $[m^3]$				
YoD	Inflow of concrete $[m^3]$	Capacity $[m^3]$	Concrete not processed $[m^3]$	Concrete processed of total inflow $[\%]$
2065	158 450	53 333	105 117	34 %
2066	75 572	53 333	22 239	71 %
2067	171 837	53 333	118 504	31 %
2068	105 770	53 333	52 437	50 %
2069	58 805	53 333	5 472	91 %
2070	63 946	53 333	10 613	83 %
2071	65 182	53 333	11 849	82 %
2072	18 931	18 931	0	100 %
2073	30 054	30 054	0	100%
2074	33 780	33 780	0	100%
TOT	**782 387**	**456 095**	-	**58.2 %**

Table 9: Total inflow of concrete to Vikan annually and the share that can effectively be processed due to area restrictions for the 2 m scenario.

	Resource park: Vikan Approx. size: 40 ha Processing capacity, 2 m scenario: 267 667 $[m^3]$			
YoD	Inflow of concrete $[m^3]$	Capacity $[m^3]$	Surplus volume available for processing $[m^3]$	Concrete processed of total inflow $[\%]$
2065	158 450	266 667	108 217	100 %
2066	75 572	266 667	191 095	100 %
2067	171 837	266 667	94 830	100 %
2068	105 770	266 667	160 897	100 %
2069	58 805	266 667	207 862	100 %
2070	63 946	266 667	202 721	100 %
2071	65 182	266 667	201 485	100 %
2072	18 931	266 667	247 736	100 %
2073	30 054	266 667	236 613	100%
2074	33 780	266 667	232 887	100%
TOT	**782 387**	**2 666 670**	**-**	**100 %**
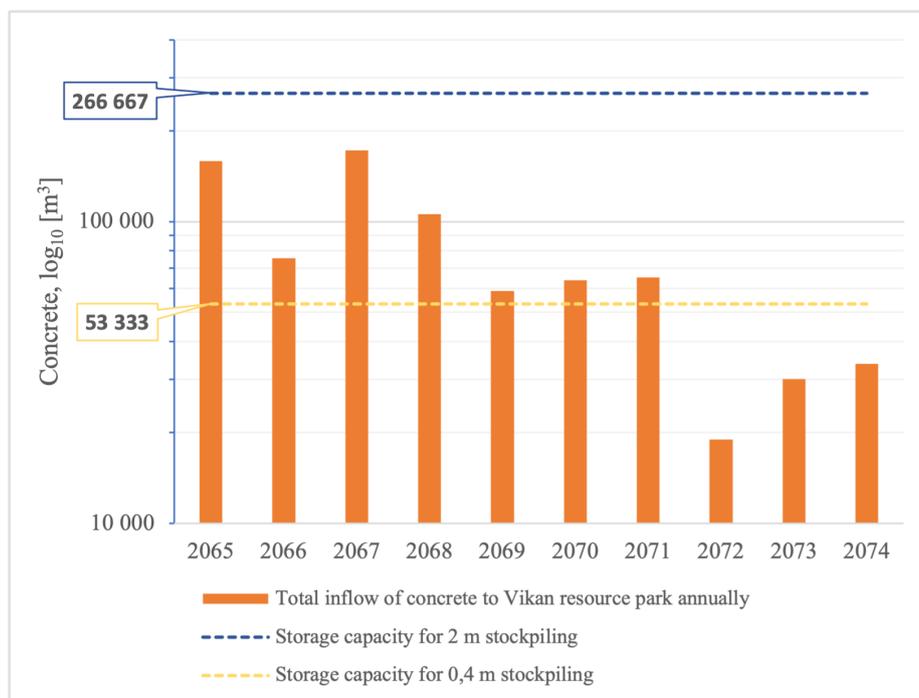
Figure 13: The total amount of concrete transported to Vikan resource park annually, in relation to the processing capacity for the two stockpiling scenarios.

4.4.3 Net-emissions: Vikan

The following section presents net-emissions for the processed concrete at Vikan. In figure 14 the net-emissions for the 0.4 m stockpiling are presented. In this case the emissions from processing the concrete are larger than the potential carbon sink, leading to CO_2 emissions ranging from 32 tons for 2072 up to 103 tons for 2069. The variation is due to the amount of concrete varying over the years. The lower amount of concrete for the latter years 2072-2074 is attributable to a lower amount of buildings being completed these years. The low variation in net emissions for 2065-2071 is due to the capacity limit of 53 333 m^3 being reached these years, see figure 13. Excess concrete which can't be processed due to capacity constraints wont be accounted for when calculating sequestration potential and process emissions. For the aggregated emissions, the demolition process is the largest contributor to CO_2, see appendix A1. Demolition, along with the other emission posts, highlight where measures can be taken to mitigate emissions as to increase the net-sequestration and the environmental benefits. Demolition, along with the other emission posts, highlight where measures can be taken to mitigate emissions as to increase the net-sequestration and the environmental benefits.

In figure 15 a net-gain in CO_2 sequestration can be seen for all years. The larger CO_2 values, compared to the emissions, are in part attributed to the larger DoC for the 2 m scenario, but also due to Vikan being able to process all concrete that is sent to it, meaning that more concrete can be utilized as a carbon sink. As for the 0.4 m scenario, the demolition emissions are the largest, see appendix table A2, followed by loader emissions, contributing 54.6% and 27.6 % of the total emissions for the 2 m scenario respectively.

	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074
CO2 emissions	1 071	1 086	1 078	1 083	1 092	1 088	1 088	383	611	684
CO2 sequestration	- 989	- 989	- 989	- 989	- 989	- 989	- 989	- 351	- 557	- 626
Net emissions	82	98	90	94	103	100	99	32	54	58
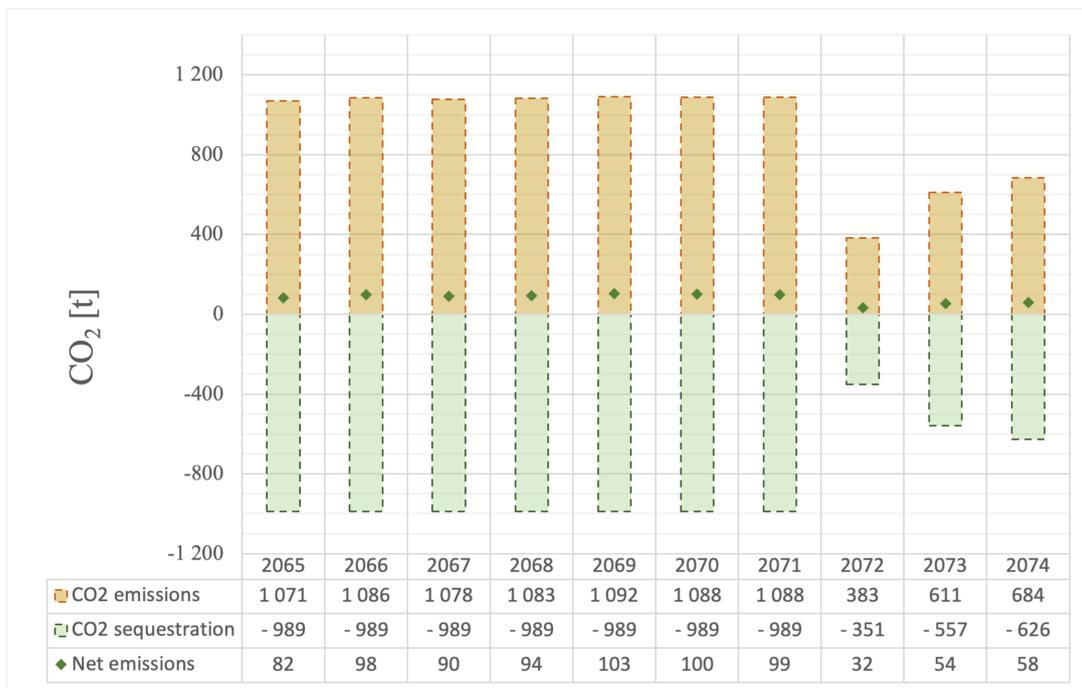
Figure 14: Net emissions for Vikan for 0.4 m stockpiling scenario.
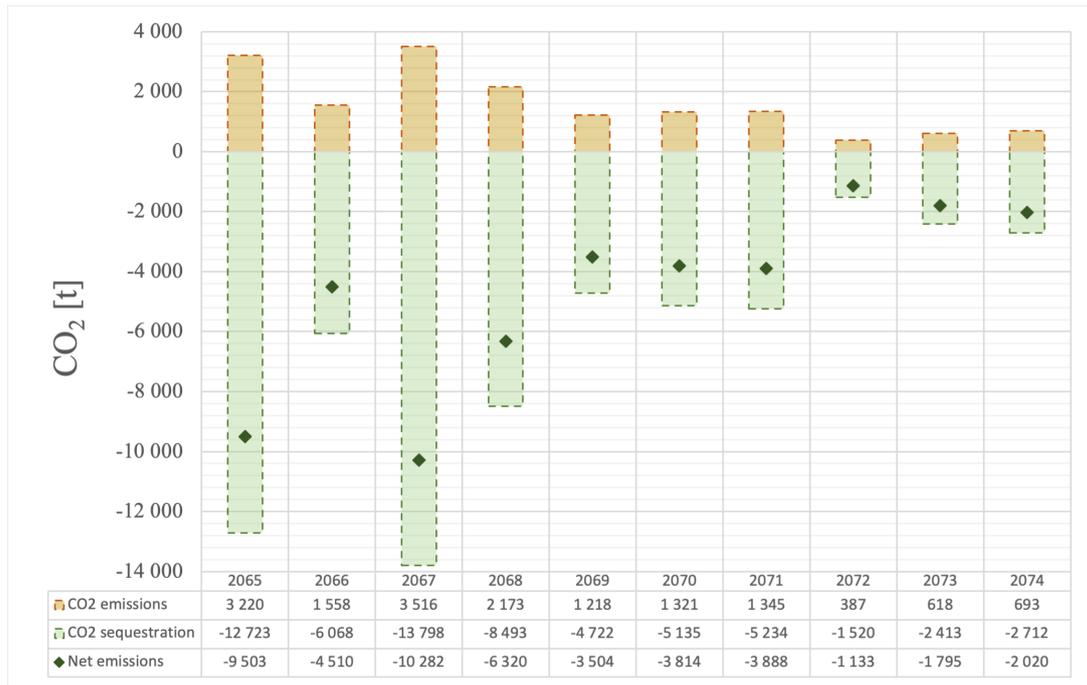
Figure 15: Net emissions for Vikan for 2 m stockpiling scenario.

4.4.4 Kållered resource park

Figure 16 visualize the results for both scenarios for Kållered resource park. It can be seen that it is able to process 100% of the inflow of concrete for all years, for both scenarios. This result is a combination of the low inflow of concrete to Kållered, see table 10 and table 11, and the large processing capacity of Kållered due to its size of 42 ha. An important comment is that due to Kållereds location in the far south of Gothenburg, see figure 10, it is further away from most of the buildings investigated in this thesis in comparison to Vikan and Gunnilse. While it recieves miniscule amounts of concrete compared to its processing capacity, this opens up an opportunity for processing excess concrete from other resource parks, see 4.4.8 for comments on this.

Table 10: Total inflow of concrete to Kållered annually and the share that can effectively be processed due to area restrictions for the 0.4 m scenario.

YoD	Inflow of concrete $[m^3]$	Capacity $[m^3]$	Surplus volume available for processing $[m^3]$	Concrete processed of total inflow $[\%]$
Resource park: Kållered Approx. size: 42 ha Processing capacity, 0.4 m scenario: 56 000 $[m^3]$				
2065	18 709	56 000	37 291	100 %
2066	8 801	56 000	47 199	100 %
2067	-	56 000	56 000	100 %
2068	5 136	56 000	50 864	100 %
2069	1 128	56 000	54 872	100 %
2070	18 557	56 000	37 443	100 %
2071	-	56 000	56 000	100 %
2072	-	56 000	56 000	100 %
2073	-	56 000	56 000	100%
2074	-	56 000	56 000	100%
TOT	**52 331**	**560 000**	-	**100 %**

Table 11: Total inflow of concrete to Kållered annually and the share that can effectively be processed due to capacity restrictions for the 2 m scenario.

			Resource park: Kållered Approx. size: 42 ha Processing capacity, 2 m scenario: 280 000 $[m^3]$	
YoD	Inflow of concrete $[m^3]$	Capacity $[m^3]$	Surplus volume available for processing $[m^3]$	Concrete processed of total inflow $[\%]$
2065	18 709	280 000	261 291	100 %
2066	8 801	280 000	271 199	100 %
2067	-	280 000	280 000	100 %
2068	5 136	280 000	274 864	100 %
2069	1 128	280 000	278 872	100 %
2070	18 557	280 000	261 443	100 %
2071	-	280 000	280 000	100 %
2072	-	280 000	280 000	100 %
2073	-	280 000	280 000	100%
2074	-	280 000	280 000	100%
TOT	**52 331**	**2 800 000**	**-**	**100 %**
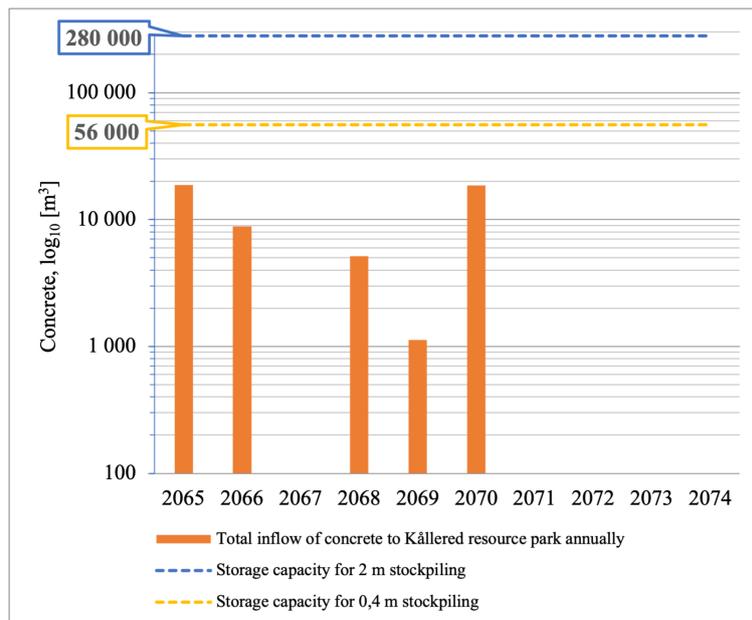
Figure 16: The total amount of concrete transported to Kållered resource park annually, in relation to the processing capacity for each natural carbonation scenario.

4.4.5 Net-emissions: Kållered

In the case for Kållered 0,4 m scenario, there is a net gain in CO_2 sequestration for all years that it recieves concrete. As the net-emissions are similar in characteristics to the 0.4 m scenario for Vikan, see figure 14 for comparison. Due to the low DoC in this scenario, the net emissions will subsequently be smaller. As Kållered will have the capacity to process all concrete it receives, the difference in net-emissions between the two scenarios are very clear when comparing figure 17 with figure 18. As it is the same amount of concrete that is processed in both scenarios, the emissions are equally large, but due to the 2m stockpiling scenario having a DoC of 85% the net savings of CO2 are substantially higher. Here it clearly shows what impact the DoC has, not only on amounts CO2 sequestrated but also from a planning perspective by knowing the time it takes to reach a certain DoC,

	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074
▣ CO2 emissions	385	181	-	106	23	381	-	-	-	-
▣ CO2 sequestration	- 606	- 285	-	- 166	- 37	- 601	-	-	-	-
◆ Net emissions	- 212	- 101	-	- 58	- 13	- 212	-	-	-	-
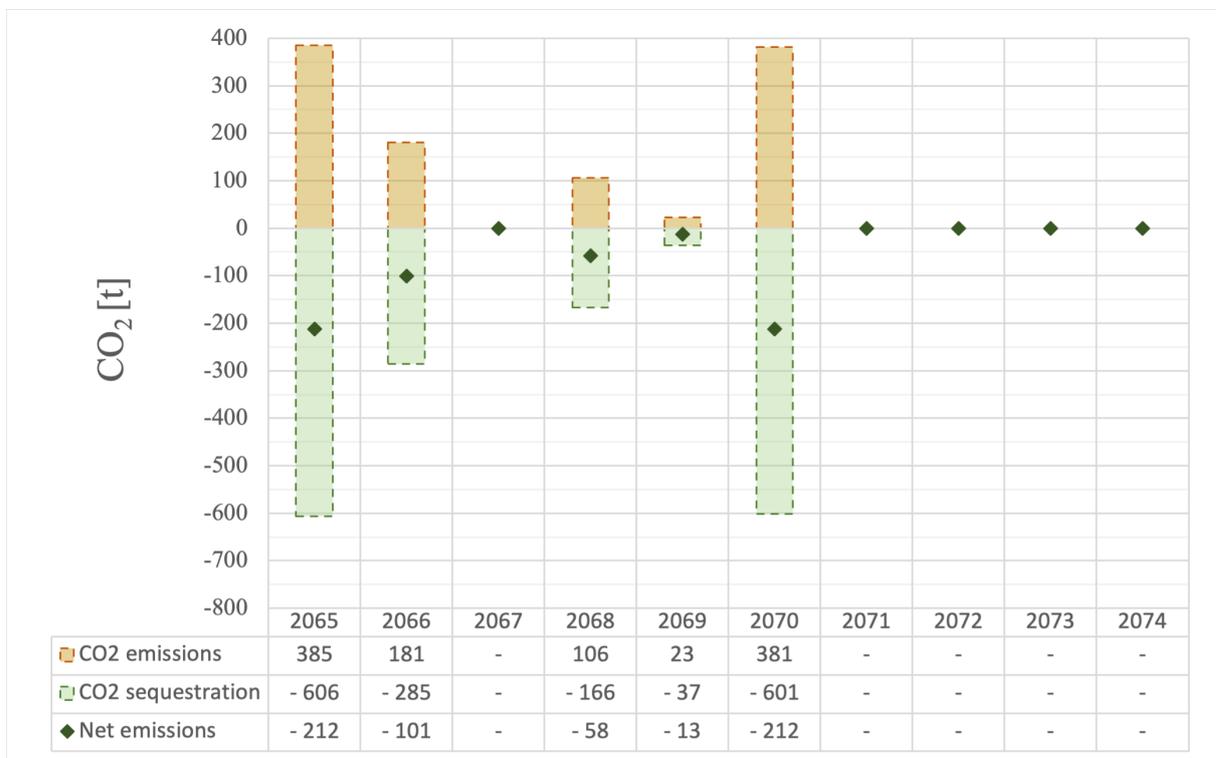
Figure 17: Net emissions for Kållered for 0.4 m stockpiling scenario.
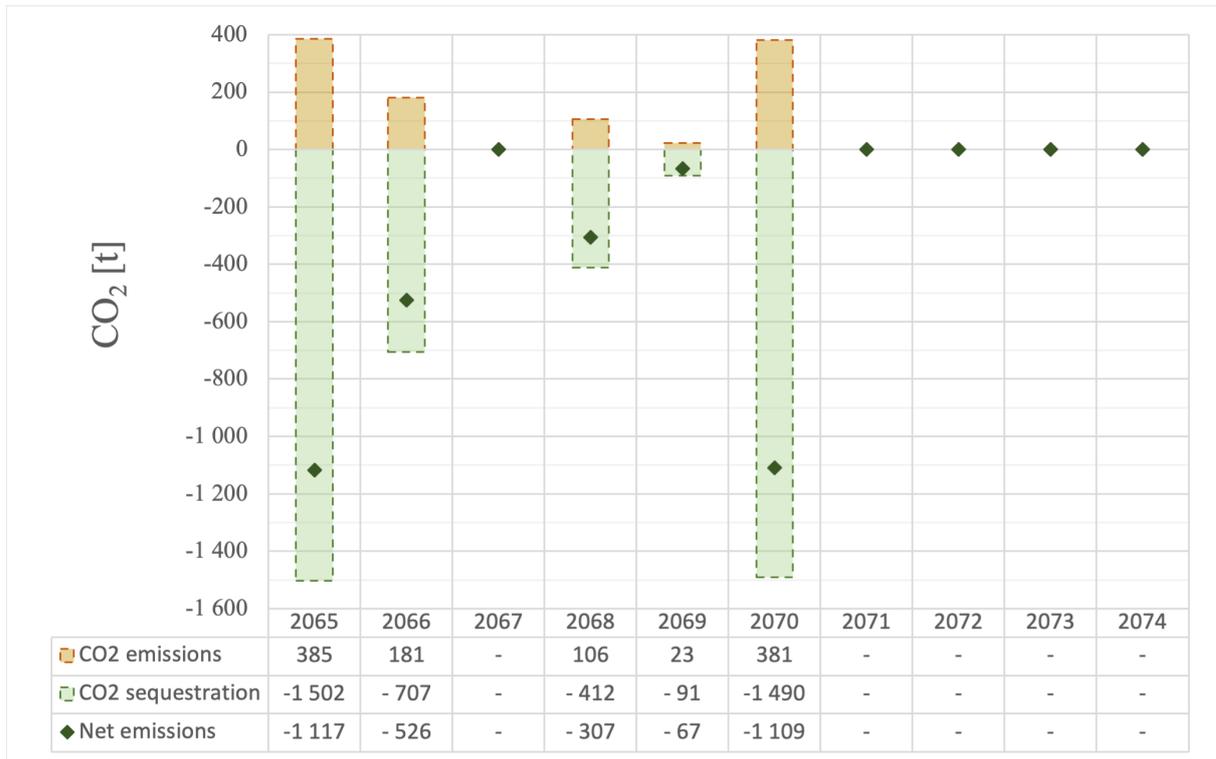
Figure 18: Net emissions for Kållered for 2 m stockpiling scenario.

4.4.6 Gunnilse resource park

Table 13 illustrates the scenario using the dimensions for 2 m stockpiles and it can be observed that there won't be adequate space for processing the concrete inflow during the years 2067-2072 largely due to the fact that Gunnilse is operating on a smaller area of 5 ha compared to the other resource parks.

Table 12: Total inflow of concrete to Gunnilse and the share that can effectively be processed due to area restrictions for the 0.4 m scenario.

Resource park: Gunnilse Approx. size: 5 ha Processing capacity, 0.4 m scenario: 6 667 $[m^3/\text{yr}]$			
YoD	Inflow of concrete $[m^3]$	Capacity $[m^3]$	Concrete not processed $[m^3]$	Concrete processed of total inflow $[\%]$
2065	8 909	6 667	2 242	74.8 %
2066	8 207	6 667	1 540	81.2 %
2067	48 376	6 667	41 709	13.8 %
2068	119 904	6 667	113 237	5.6 %
2069	70 173	6 667	63 506	9.5 %
2070	138 291	6 667	131 604	4.8 %
2071	130 602	6 667	123 935	5.1 %
2072	73 323	6 667	66 656	9.1 %
2073	32 894	6 667	26 227	20.3 %
2074	23 918	6 667	17 251	27.9 %
TOT	**654 598**	**66 670**	-	**10.2 %**

Table 13: Total inflow of concrete to Gunnilse annually and the share that can effectively be processed due to area restrictions for the 2 m scenario.

| YoD	Inflow of concrete $[m^3]$	Capacity $[m^3]$	Concrete not processed $[m^3]$	Concrete processed of total inflow $[\%]$
Resource park: Gunnilse Approx. size: 5 ha Processing capacity, 2 m scenario: 33 333 $[m^3/\text{yr}]$				
2065	8 909	8 909	0	100 %
2066	8 207	8 207	0	100 %
2067	48 376	33 333	15 043	68.9 %
2068	119 904	33 333	86 571	27.8 %
2069	70 173	33 333	36 840	47.5 %
2070	138 291	33 333	104 958	24.1 %
2071	130 602	33 333	97 269	25.5 %
2072	73 323	33 333	39 990	45.5 %
2073	32 894	32 894	0	100 %
2074	23 918	23 918	0	100 %
TOT	**654 598**	**273 926**		**41.8 %**
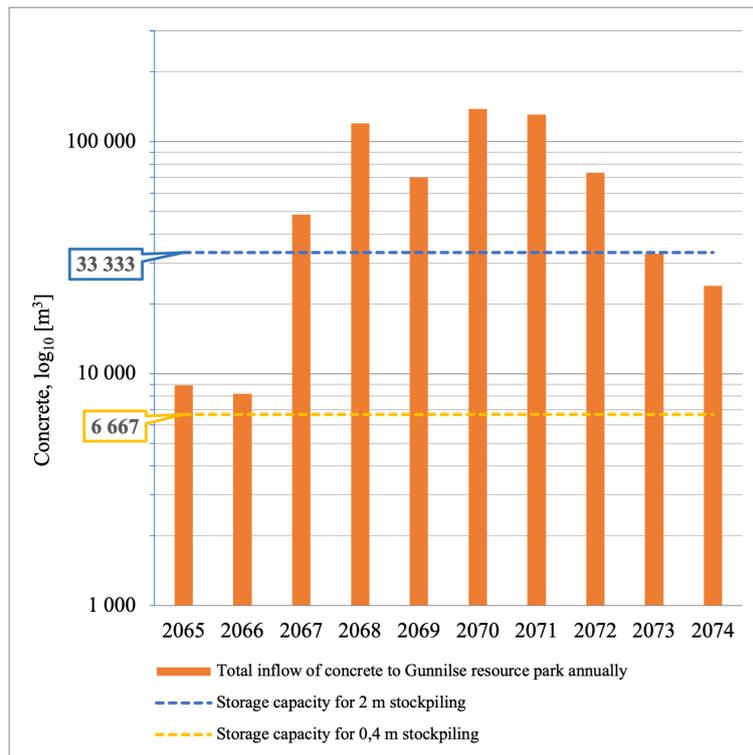
Figure 19: The total amount of concrete transported to Gunnilse resource park annually, in relation to the processing capacity for each natural carbonation scenario.

4.4.7   Net-emissions: Gunnilse

The results for the net-emissions related to Gunnilse resource park are presented in figure 20 for the 0.4 m scenario and figure 21 for the 2 m scenario. Figure 20 show that there will be net-emissions of 11-14 tons of CO_2 for the 0.4 m scenario. This is both a consequence of the DoC of 34.3 % compared to that of 85 % for the 2 m scenario in figure 21, and due to the processing capacity being exceeded for all years in the 0.4 m scenario.

The 2 m stockpiling scenario results in 214-870 tons of CO_2 being sequestrated, depending on how much concrete that is processed. For the years 2067-2073 the amount of concrete that is transported to Gunnilse exceeds its processing capacity of 33 333 m^3. The difference in net-emissions for these years, ca 10 tons, is attributed to a difference in transport distance over the years, see A6.

	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074
CO2 emissions	136	136	136	135	136	135	137	137	135	136
CO2 sequestration	- 124	- 124	- 124	- 124	- 124	- 124	- 124	- 124	- 124	- 124
Net emissions	12	12	12	12	12	12	14	14	11	13
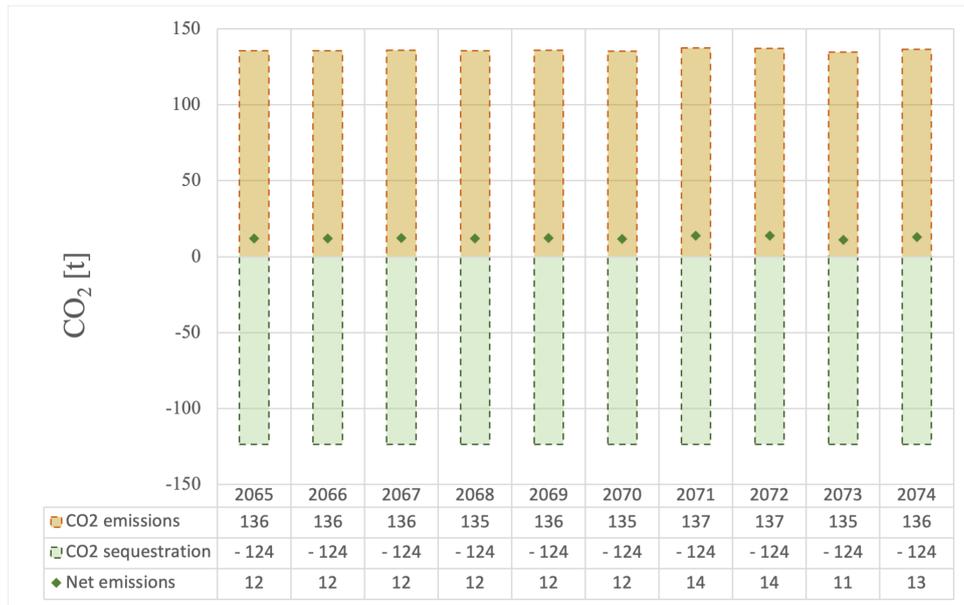
Figure 20: Net emissions for Gunnilse for 0.4 m stockpiling scenario.

	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074
CO2 emissions	177	163	663	662	664	661	671	671	650	478
CO2 sequestration	- 409	- 377	-1 531	-1 531	-1 531	-1 531	-1 531	-1 531	-1 511	-1 099
Net emissions	- 232	- 214	- 868	- 870	- 867	- 870	- 860	- 861	- 861	- 620
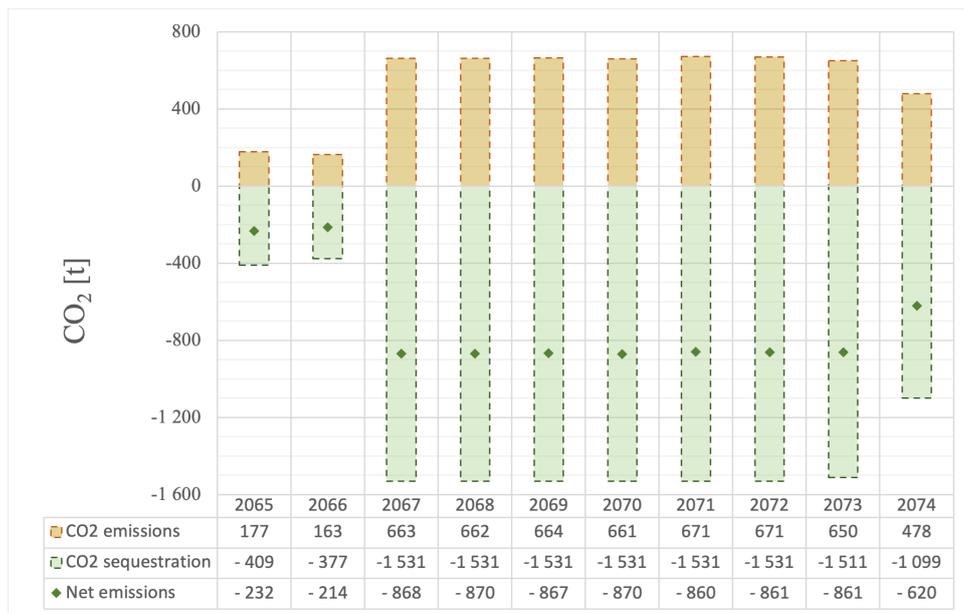
Figure 21: Net emissions for Gunnilse for 2 m stockpiling scenario.

4.4.8 Utilizing surplus volumes

The method of measuring mean average linear distances, most concrete from demolished buildings will be allocated to Vikan as it is more centrally located compared to Kållered and Gunnilse. Due to this, there will be scenarios where resource parks get a larger inflow of concrete than they are able to process, and some scenarios where the capacity won't be exceeded and thus have a surplus volume available. A re-evaluation of certain transports could result in sending excess concrete that cant

be processed to sites with a surplus volume available. This is illustrated in 16, where there are years of no concrete inflow, and years where there is potential to stockpile larger volumes.

4.5 CO_2 donors and Fastcarb technology

The identified industries that could provide an inflow of CO_2 to the Fastcarb units are presented in figure 22.

However, not all sites emit CO_2 and not all sites provided sufficient data for further analysis. The heaviest emitters operates as combustion plants and oil refineries, with various compositions of emissions in the industries flue gases. This thesis will only regard the CO2 emitted from these sites. Furthermore, The sites should preferably be chosen with distances in mind to optimize logistical efficiencies parallel with environmental sustainability objectives.

Moreover, a single Fastcarb unit has a constant annual processing capacity of 1 897.5 m^3 with the ability to capture between 25-40 kg of CO_2, see table 2. The capacity of the units remain constant over the years 2065-2074 which is why the net emissions only exhibit a slight variation. This variation is attributed to the calculations being based on different mean average transportation distances. As the thesis progressed, it was clear that transportation emissions were only a small share in comparison to the other emission posts, especially demolition, see appendix A1 through A6. If the transportation emissions are offset by the carbon sequestration, then it can be worth exploring CO_2-donors located further away in order to increase the processing capacity for the Fastcarb scenario.

More noticeably is the small volume of concrete that a Fastcarb unit can process. However, if there were to be a smaller stream of demolished concrete to the resource parks, which may very well be the case since the assumption of a 100 year lifetime is yet to be proven, then a Fastcarb unit would possibly be a more viable technology, due to its rapid carbonation. Adding to this, if the carbonated CA is used as an input in when producing concrete, it can reduce the need for virgin material extraction, strongly connected to the goal set by EU to implement aa environmentally sound management of construction demolition waste Caro et al., 2024.

When comparing these three scenarios, a Fastcarb unit that can sequestrate 25-40 kg CO_2 per t concrete with an annual capacity of 3 036 tons falls short when compared to stockpiling 2 m with a DoC of 85% for 6 months. Attributed mainly to the high DoC and amounts of concrete that can be processed with natural carbonation, which is closer to the operational realities of the aggregate industry. However, if it would be a case with lower DoC, smaller stockpiles and longer time-scales for sequestrating CA, such as the 0.4 m scenario, then a Fastcarb unit could be deemed more attractive.
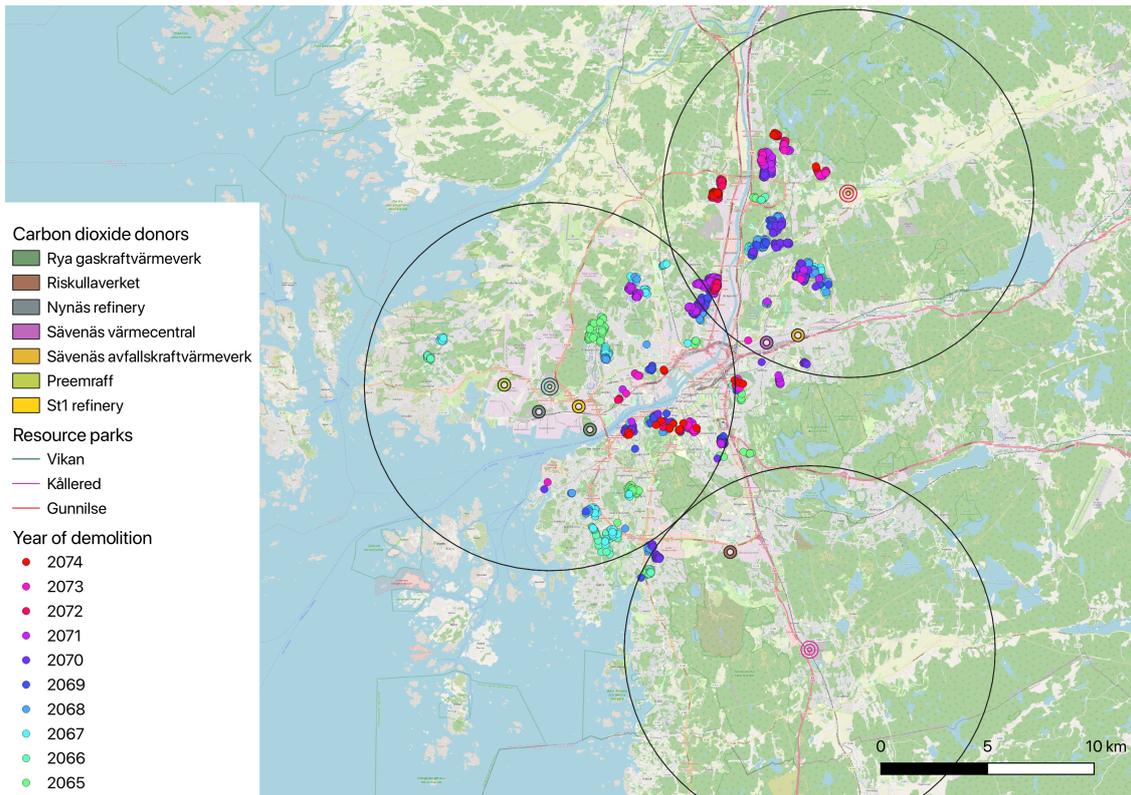
Figure 22: Map over Gothenburg with plotted buildings, resource parks and CO2-donors. Picture captured from QGIS

4.5.1 Fastcarb: Vikan

In figure 23 the processing capacity of four Fastcarb units is illustrated. Vikan, located in an industrial area where four of the identified potential CO2 donors operate, see figure 22, presents an opportunity to increase the share of processed concrete for that site. With four Fastcarb units a total of 7 590 m^3 of concrete can be processed annually, which however still is not enough compared to the amount of concrete that the resource park recieve every year.
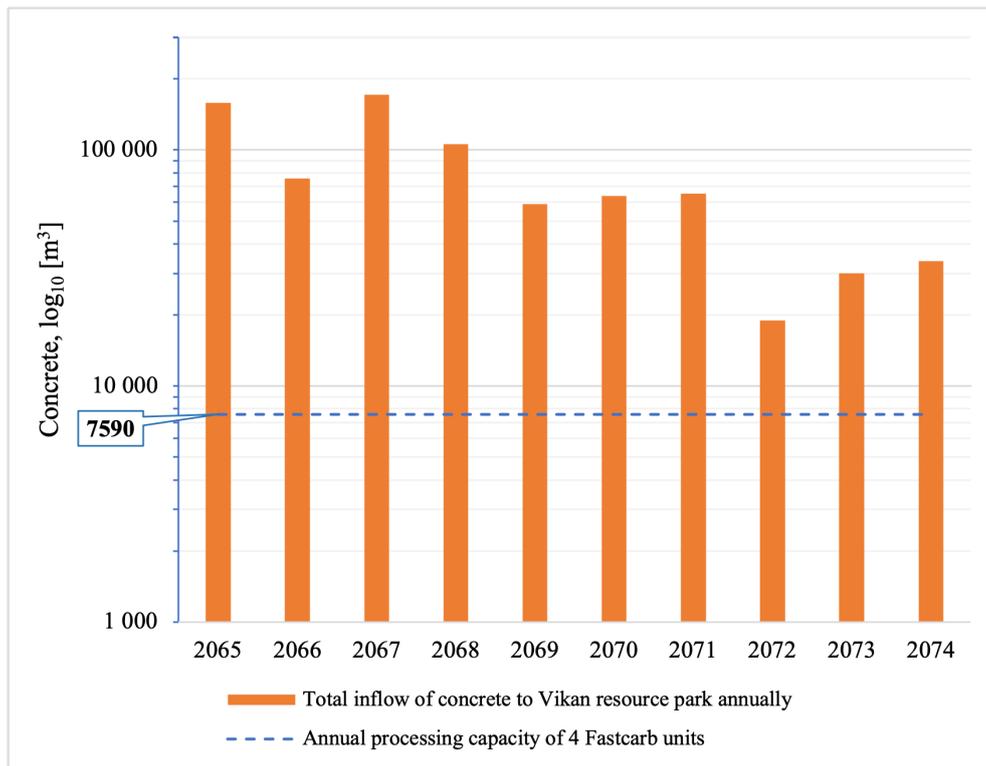
Figure 23: A Fastcarb units processing capacity in relation to inflow of concrete at Vikan resource park.

4.5.2 Fastcarb: Kållered

In figure 24 the processing capacity of a single Fastcarb unit operating at Kållered is illustrated. For Kållered there is only one identified emittor near-by, see figure 22, Riskullaverket. As previously mentioned, due to the location, year 2067 and 2071-2074 will result in no inflow of concrete to the resource park. However, as the Fastcarb unit only processes a small amount of the previous years volumes, there is a potential to use the excess non-processed concrete the years where there is no inflow of concrete.
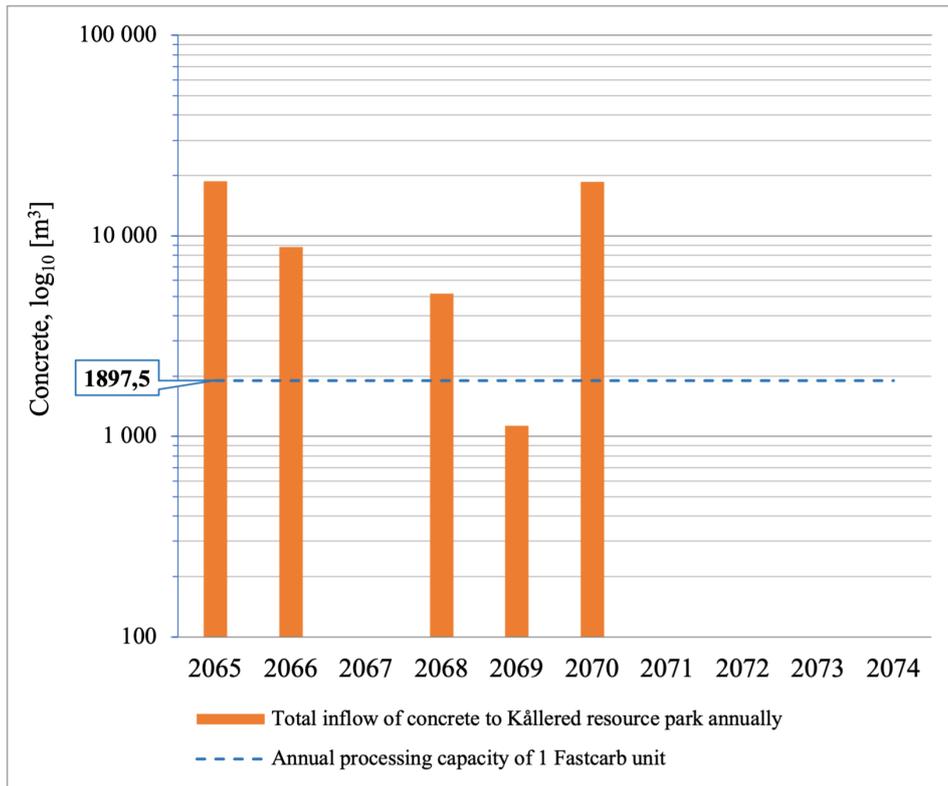
Figure 24: A Fastcarb units processing capacity in relation to inflow of concrete at Kållered resource park

4.5.3 Fastcarb: Gunnilse

In figure 24 the processing capacity of a two Fastcarb units operating at Gunnilse is illustrated as two nearby potential CO2 donors where identified. This increases the annual processing capacity of the concrete sent from Gunnilse resource park to 3 795 m^3.
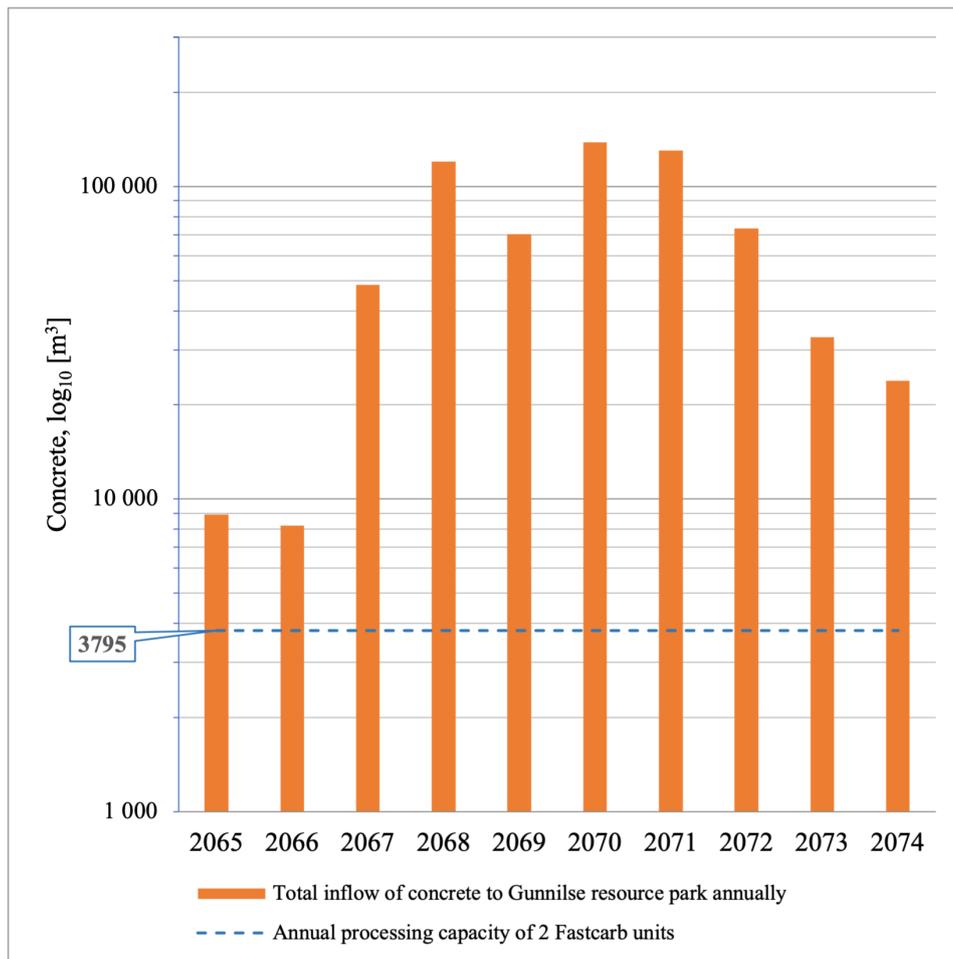
Figure 25: A Fastcarb units processing capacity in relation to inflow of concrete at Gunnilse resource park

4.6 Net-emissions: Fastcarb technology

Due to the Fastcarb unit processing an equal amount annually, sequestrating 25-40 kg CO2 / t concrete, there will only be slight variations of net emissions, which are attributed to different mean average distances. Interestingly, a Fastcarb unit has a DoC ranging from 37-59 %, which at its lowest is still higher than the scenario of 0.4 m stockpiling which generates a DoC of 34.4%, indicating that it sequestrates more kg CO_2 / t concrete, and in a much shorter time span as well. See table 14 for aggregated performance results on a Fastcarb unit.

4.7   Aggregated results

In table 14 the aggregated results are presented in kg CO_2 emitted and seques-
trated per ton of processed concrete. It is clear that the scenario of 2 m stockpiling
sequestrate more than what is possible during the use-phase with a maximum se-
questration of 37.4 kg CO_2 / t concrete. Even if a Fastcarb unit is used and perform
at 40 kg CO_2 / t concrete it can at most sequestrate 26.2 kg when accounted for
process emissions. The 0.4 m scenario is the poorest choice when accounting for
process emissions with a net sequestration of 7.1 kg CO_2 / t concrete. The use-
phase sequestration is in the table for reference, but it may not be truly comparable
as this thesis account for all emissions in relation to natural carbonation of crushed
concrete and using Fastcarb technology, see figure 8 for the system boundaries. If
removing the demolition emissions from the use-phase sequestration it would result
in a net sequestration of 1.33 kg CO_2 / t concrete highlighting the large emissions
connected to demolition practices.

When accounting for how time consuming these different practices are, the Fastcarb
unit may be a viable choice as it sequestrate CO_2 much faster than the process of
natural carbonation. A barrier for effiency is its limited capacity and man hours
needed for loading and unloading concrete. Natural carbonation occurs constantly
and without the need for human interaction, beside loading the concrete into piles.
If a suitable area of land is available it may be a viable practice for storing CO_2,
which then is perpetually locked in as $CaCO_3$. More research is however needed in
how the natural carbonation performance is affected on larger stockpiles as smaller
stockpiles will consume large land areas, which may make it unattractive for use.
The two natural carbonation scenarios used in this thesis are however contradictive,
with the smaller fractions (0.4 m scenario) consuming less CO_2 than larger stockpiles
(2 m scenario), which should not generally be the case according to literature (SIS,
2019; Stripple et al., 2018).

Table 14: Aggregated results for each scenario.

Scenario	Emissions [kg CO_2 / t concrete]	Sequestration [-kg CO_2 / t concrete]	Net emissions [kg CO_2 / t concrete]	Time requirement
Use-phase	0	-8.33	**-8.33**	100 [yr]
Vikan 0.4 m	13.1	-20.3	**-7.1**	1,5 [yr]
Vikan 2 m	12.8	-50.2	**-37.4**	0,5 [yr]
Kållered 0.4 m	13.1	-20.3	**-7.1**	1,5 [yr]
Kållered 2 m	12.9	-50.2	**-37.3**	0,5 [yr]
Gunnilse 0.4 m	12.7	-20.3	**-7.5**	1,5 [yr]
Gunnilse 2 m	12.5	-50.2	**-37.7**	0,5 [yr]
Fastcarb (1 unit)	13.2-13.5	-40 - (-25)	**-26.2 - (-11.2)**	1,5 [h]

5

Conclusion

The studied concrete buildings sequestrate 12.4% of CO_2 emissions deriving from the calcination process over a service life of 100 years. Due to carbonation being a non-linear process the carbonation most likely occurs during the first 50 years in concrete structures, before the process is slowed down due to increased density by the formation of $CaCO_3$. Thus, the largest carbon capture potential is at the EoL when the concrete is crushed and uncarbonated surfaces are exposed to atmospheric CO_2, promoting further sequestration. From the studied scenarios, this was found to be either a DoC of 34.3% or 85%, which generates uncertainty in determining carbon uptake in stockpile scenarios as there is a large spread in the literature data.

Emissions from demolition proved substantial in this thesis, accounted for 53-57.5% of process emissions in each scenario of natural carbonation. Depending on where emissions are allocated, the net sequestration of concrete can vary greatly. Transportation emissions were relatively small, only 4-7%, largely attributed to demolition having a huge impact. For the Fastcarb scenario, transport emissions increased to 7.2-12.5% due to the extra transportation distance to the CO_2 donors. If transport emissions are offset by sequestration, it could open a discussion about transporting the CA further distances for processing, if there is a lack of space for storage in Gothenburg. Crushing emissions vary between 12.7-15.8 % of the total emissions, and loader emissions vary between 18.2-27.6 %.

It is evident that there isn't enough space in the identified resource parks to process the stockpiling scenarios. While the Fastcarb carbonates concrete at a faster rate than natural carbonation, its processing capacity is low compared to the total inflow of concrete in this study, leading to net emission closer to net zero than for the 2 m scenario. For industrial scale purposes, upscaling the processing capacity of the Fastcarb would be desirable due to the large outflow of concrete that occurs during demolitions of concrete infrastructure, reducing the need for large intermediate storage areas and increasing the time efficiency of the carbonation process. The Fastcarb scenario is speculative as there are many uncertainties regarding an industrial symbiosis with the identified industries such as logistics, to whom the sequestration should be allocated, and economic perspectives, to name a few. Another aspect is the lifespan of the MP buildings. This report is constructed around an assumed lifetime of 100 years, but this alone is a complex topic that might be impossible to determine with any certainty.

In a scenario where the carbonation occurs naturally, the conditions will be dictated

by the climate and external environment. These can't always be controlled but adapted to. The time span of the carbonation process is however difficult to affect without technological solutions, such as Fastcarb. Natural carbonation is however a relatively easy way to utilize CA as a carbon sink.

The contradictory findings in the literature highlight the complexity of the carbonation process and the influence of factors such as the size of the concrete fractions, conditions of storage as well as the methods of measuring CO_2 uptake. This underscores a need for further studies and tests to accurately determine the carbonation degree and the optimal dimensions of the stockpiles for promoting carbonation. This information is vital for planning and running operations to maximise CO_2 sequestration in concrete aggregates.

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A
Appendix

A.1 Process emissions, Vikan 0.4 m

Table A1: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Vikan. 0.4 m scenario.

	Resource park: Vikan Scenario: 0.4 m			
YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
2065	597	45	264	164
2066	597	61	264	164
2067	597	52	264	164
2068	597	57	264	164
2069	597	66	264	164
2070	597	63	264	164
2071	597	62	264	164
2072	212	19	94	58
2073	337	33	149	92
2074	378	35	167	104
TOT	5 108	492	2 260	1 403
Share [%]	55.1	5.3	24.3	15.3
Sum [t]	**9 264**			

A.2 Process emissions, Vikan 2 m

Table A2: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Vikan. 2 m scenario.

	Resource park: Vikan Scenario: 2 m			
YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
2065	1 775	134	897	414
2066	846	86	428	197
2067	1 925	169	973	449
2068	1 185	113	599	276
2069	659	73	333	154
2070	716	75	362	167
2071	730	76	369	170
2072	212	19	107	49
2073	337	33	170	79
2074	378	35	191	88
TOT	8 762	812	4 431	2 043
Share [%]	54.6	5.1	27.6	12.7
Sum [t]	**16 048**			

A.3   Process emissions, Kållered 0.4 m

Table A3: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Kållered. 0.4 m scenario.

	Resource park: Kållered Scenario: 0.4 m			
YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
2065	210	28	99	58
2066	99	12	47	27
2067	0	0	0	0
2068	58	8	27	16
2069	13	2	6	3
2070	208	27	98	57
2071	0	0	0	0
2072	0	0	0	0
2073	0	0	0	0
2074	0	0	0	0
TOT	586	77	277	161
Share [%]	53	7	25	15
Sum [t]	**1 100**			

A.4 Process emissions, Kållered 2 m

Table A4: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Kållered. 2 m scenario.

	Resource park: Kållered Scenario: 2 m			
YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
2065	210	28	99	49
2066	99	12	47	23
2067	0	0	0	0
2068	58	8	27	13
2069	13	2	6	3
2070	208	27	98	48
2071	0	0	0	0
2072	0	0	0	0
2073	0	0	0	0
2074	0	0	0	0
TOT	586	77	277	137
Share [%]	54	7	26	13
Sum [t]	**1 076**			

A.5   Process emissions, Gunnilse 0.4 m

Table A5: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Gunnilse. 0.4 m scenario.

	Resource park: Gunnilse Scenario: 0.4 m			
YoD	Demolition emissions $[t\ CO_2]$	Transport emissions $[t\ CO_2]$	Loader emissions $[t\ CO_2]$	Crushing emissions $[t\ CO_2]$
2065	75	5	35	21
2066	75	5	35	21
2067	75	5	35	21
2068	75	5	35	21
2069	75	5	35	21
2070	75	5	35	21
2071	75	7	35	21
2072	75	7	35	21
2073	75	4	35	21
2074	75	6	35	21
TOT	750	55	350	210
Share [%]	55	4	26	15
Sum [t]	**1 359**			

A.6   Process emissions, Gunnilse 2 m

Table A6: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Gunnilse. 2 m scenario.

YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
2065	100	7	47	23
2066	92	6	43	21
2067	373	27	176	87
2068	373	25	176	87
2069	373	27	176	87
2070	373	24	176	87
2071	373	35	176	87
2072	373	34	176	87
2073	368	21	174	86
2074	268	22	126	62
TOT	3 068	228	1 448	115
Share [%]	56.2	4.2	26.5	13.1
Sum [t]	**5 460**			

(Table header: Resource park: Gunnilse — Scenario: 2 m)

A.7   Process emissions, Fastcarb Vikan

Table A7: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Vikan. Fastcarb scenario (**4 pcs**).

YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
Resource park: Vikan / Scenario: Fastcarb				
2065	85	8.9	28.7	23.4
2066	85	11.2	28.7	23.4
2067	85	10	28.7	23.4
2068	85	10.6	28.7	23.4
2069	85	11.9	28.7	23.4
2070	85	11.4	28.7	23.4
2071	85	11.4	28.7	23.4
2072	85	10	28.7	23.4
2073	85	10.8	28.7	23.4
2074	85	10.3	28.7	23.4
TOT	850	106.6	287	234
Share [%]	57.5	7.2	19.5	15.8
Sum [t]	**1 477.6**			

A.8 Process emissions, Fastcarb Kållered

Table A8: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Kållered. Fastcarb scenario (**1 pc**).

Resource park: Kållered Scenario: Fastcarb			
YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
2065	21.3	4.8	7	6
2066	21.3	4.6	7	6
2067	0	0	0	0
2068	21.3	4.8	7	6
2069	21.3	4.7	7	6
2070	21.3	4.6	7	6
2071	0	0	0	0
2072	0	0	0	0
2073	0	0	0	0
2074	0	0	0	0
TOT	106.3	23.4	36	29
Share [%]	54.3	12	18.2	15.5
Sum [t]	**194.7**			

A.9 Process emissions, Fastcarb Gunnilse

Table A9: Emissions from demolishing MP buildings and from crushing concrete into smaller fractions for carbonation at Gunnilse. Fastcarb scenario (**2 pcs**).

	Resource park: Gunnilse Scenario: Fastcarb			
YoD	Demolition emissions [$t\ CO_2$]	Transport emissions [$t\ CO_2$]	Loader emissions [$t\ CO_2$]	Crushing emissions [$t\ CO_2$]
2065	42.5	7.9	14.3	11.7
2066	42.5	7.8	14.3	11.7
2067	42.5	7.9	14.3	11.7
2068	42.5	7.7	14.3	11.7
2069	42.5	8	14.3	11.7
2070	42.5	7.7	14.3	11.7
2071	42.5	8.8	14.3	11.7
2072	42.5	8.8	14.3	11.7
2073	42.5	7.4	14.3	11.7
2074	42.5	8.3	14.3	11.7
TOT	425	80.3	143	117
Share [%]	55.5	10.5	18.7	15.3
Sum [t]	**765.3**			