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Acknowledgements

This thesis marks the completion of my master studies. Throughout this thesis I have gained a deeper understanding of the properties, advantages, and limitations of low carbon concrete. I chose a thesis with a focus on low carbon concrete as a topic since it's likely that this will be one of the main materials used in my future work as a civil engineer.

First and foremost, I would like to thank all my fellow students. You have been a great source of inspiration and motivation throughout the good and the challenging times. A special thanks goes out to my family and friends. Your support the last few years has kept me focused and motivated. I would also like to express my sincere gratitude to my advisor, Kjell Tore. Your guidance and support the last six months has been invaluable.

Abstract

This thesis investigates the emission profiles of two types of low carbon concrete: Schwenk's low heat cement and a geopolymer cement in development from Saferock. As a basis for comparison a case scenario where a low carbon building is being built in Bergen is used. The emission calculations are based on Environmental Product Declarations (EPD's) published by EPD Norge for each material required in the concrete.

The majority of emissions from concrete production is from clinker production, which can be reduced by substituting parts of the binder with Supplementary Cementitious Materials (SCM's). SCM's are zero-emission byproducts and they are commonly used in cement production to reduce emissions. Saferock uses instead mining waste as a binder to significantly reduce emissions compared to traditional concrete types. Industries such as coal-burning power plants and iron production generate carbon-neutral byproducts used in concrete, thus reducing the cement requirement and lowering associated emissions. This offers an efficient waste management solution, although it may need to change if SCM's are not classified as carbon neutral in the future.

The study also considers the potential of using natural SCM's from Iceland which originates from volcanic eruptions as a sustainable solution. Carbon capture methods are being integrated into the cement industry, despite their high energy demands. These technologies are only beneficial when the total emissions captured are less than those produced from increased energy production. Such solutions are viable in regions like Norway where hydropower is the main energy source. The introduction of carbon taxes by the European Union (EU) to promote carbon reduction measures is also explored, along with the conversion of captured CO_2 into Sustainable Aviation Fuels (SAF). Different CO_2 storage solutions such as Carbfix in Iceland and Equinor's depleted oil and gas fields in Norway are investigated.

The results show that when comparing CO_2 emissions from Saferock's geopolymer concrete and Schwenk's low heat concrete, Saferock's concrete reduces emissions by 65.23% (excluding transportation and reinforcement) and by 43.65% when these factors are included. This marks geopolymer cement from Saferock as a superior choice in terms of CO_2 emissions for low carbon construction.

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List of Notations

CC	Carbon Capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
FA	Fly ash
$GGBS$	Ground granulated blast furnace slag
Kg	Kilogram
PFA	Pulverized fly ash
SAF	Sustainable Aviation Fuels
SCM	Supplementary Cementing Materials
SF	Silica fume
$SPECCA$	Specific Primary energy consumption
w/c	Water to cement ratio

Chapter 1

Introduction

Concrete is the most widely utilized building material in the world and about 4 billion tonnes of cement (which is a main component used in concrete) are produced annually Lehne, Johanna and Preston ,Felix (2018). The production of cement contributes to roughly 8% of the global CO_2 emissions and to be able to reach the goal of the Paris agreement, the annual emissions from the cement industries needs to be reduced by 16% by 2030 (Lehne, Johanna and Preston ,Felix 2018). Even small reductions in greenhouse gas emissions per ton of concrete can therefore have a significant positive impact on the environment (Nazari 2017). The concrete industry is therefore under pressure to find more sustainable methods of production, and there are many innovative solutions currently in development to address this challenge.

The aim of this thesis is to investigate current challenges with low carbon concrete, limitations according to the concrete standards and the likely emission reductions from using low carbon concrete per cubic meter over the next five to ten years. For this purpose two different types of low carbon concrete are investigated and compared. The concrete types are Scwhenk's low heat concrete and a geopolymer concrete in development from Saferock.
The comparison is made using a hypothetical case where a low-emission cultural center is being constructed in the city of Bergen, Norway. The required concrete volume to construct the building is calculated and used as reference for the emission calculations. Emissions from production, transportation and reinforcement are the main categories being compared and the emission properties are retrieved from available Environmental Product Declaration's (EPD's) published by EPD Norge.

The theory gives a background to concrete production, EPD's, life cycle of materials and how a low carbon concrete (also commonly known as environmental concrete) is categorized. Challenges with introducing new concrete materials is presented and it also describes different methods used to reduce emissions from the concrete industry such as carbon capture and supplementary cementitious materials. The increased energy requirement with producing low carbon concrete due to the existing carbon capture methods is also presented. How the captured carbon can be stored or utilized as a resource to replace fossil fuels in the future is outlined. The following methodology chapter goes into detail on which strength and durability classes are used, how the concrete volume is estimated and shows how the required concrete volume can be reduced by using hollow cores.

The calculated emission data shown in the results defines which carbon class each of the concrete types obtains. Emissions from each of the concretes are compared to find the most suitable concrete type for the cultural center.

Figure 1.1: Overview photo of Brevik carbon capture cement plant which shows the scale of a cement factory. The factory is under construction and will be operational in 2024 (Breivik,CCS 2023). Figure from Heidelberg Materials (2022).

Chapter 2

Literature Review

In this chapter what defines a low carbon concrete is presented and how it can be used to reduce the CO_2 footprint during construction of new buildings. This chapter will also present various methods that can be used to reduce emissions such as by replacing clinker with Supplementary cementitious materials or replacing the cement material with geopolymer cement. Carbon capture techniques, carbon storage solutions and utilization of captured CO_2 to create sustainable aviation fuels is also presented.

2.1 Concrete production

Simplified, concrete production requires cement, aggregates and water. Clinker is the main component of cement and the manufacture of clinker is responsible for more than 50% of the emissions during cement production. The production involves sintering limestone and aluminosilicate materials such as clay. The chemical reaction called the calcination process is defined by

$$CaCO_3 \rightarrow CaO + CO_2. \tag{2.1}$$

The equation shows that CO_2 is released during the production of calcium oxide (CaO). It's therefore not possible to avoid that CO_2 is produced in the process however it's possible to implement carbon capture in the clinker production.
Another option to reduce the CO_2 emissions is to reduce the amount of clinker required while achieving sufficient strength and durability of the concrete. This can be achieved by substituting parts of the clinker with supplementary cementing materials (SCM's) which are further explained in section 2.5.

2.2 Environmental Product Declaration (EPD)

According to Smeplass et al. (2020), an Environmental Product Declaration (EPD) is a necessary documentation that enables an easy and objective comparison of various products or services in terms of their environmental impact. Due to the increasing environmental concerns, it has become the norm to declare the environmental impact of a product or service using a standardized declaration.

Each construction project requires an EPD to be developed to provide an environmental profile of the product, and there are two types of EPD's available: project-specific and product-specific. Generally a product specific EPD is an EPD that is registered and approved by EPD-Norway. A project specific EPD is built upon a product specific EPD while having additional documentation requirements such as two internal corporate controllers Smeplass et al. (2020). Only approved operators/inspectors authorized by EPD Norway can create EPDs and in most cases project-specific EPDs (which are valid for 5 years) are adequate Smeplass et al. (2020). The final data from different EPD's is used to compare the environmental impacts of different products. In this thesis EPD's will be used to compare the environmental impact of different types of cement.

2.3 Life cycle assessment

To compare EPD's from different suppliers it is crucial to ensure that they are based on the same life cycle analysis. Table 2.1 displays the relevant categories for concrete. The table includes Product Stages ranging from A1-A3, Construction Processes Stage from A4-A5, Use stages from B1-B5, and End-of-life stages from C1-C4. The vertical blue boxes in each of the categories describes the content of each category.

If any parts of the life cycle categories are missing in the EPD's being compared it's possible to use an average from other products with the same material composition to assist in the comparison (Epd-norge 2023).

Product Stage			Construction Process Stage		Use Stage					End-of-Life Stage			
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Deconstuction & demolition	Transport	Waste processing	Disposal
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4

Figure 2.1: Life cycle categories. An EPD can include one or several of the categories in the life cycle. Most of the EPD's used in this thesis includes life cycle A1 to A4 (commonly called cradle to gate). Table from Epd-norge (2023).

2.4 Environmental concrete

Low carbon concrete or environmental concrete are interchangeable terms used to describe concrete with a reduced carbon footprint. One of the main contributors to low carbon concrete is by reducing the amount of clinker needed in the mixture and substituting parts with pozzolan or hydraulic binder Smeplass et al. (2020). When combined with cement and water these materials have similar binding properties. By reducing the cement content in the concrete, the amount of CO_2 emitted per m^3 of concrete is also reduced which results in a more environmentally friendly product. Pozzolans and hydraulic binders are either byproducts of other production processes or found naturally e.g. pumice found on Iceland which originates from volcanic eruptions (volcanic ash) EP Power Minerals GmbH (2023). They are also commonly referred to as Supplementary Cementing Materials (SCM).

Since SCM's are byproducts of processes such as coal burning power plants or steel production, their use in concrete manufacturing is considered a form of waste management. Utilizing these materials in concrete production generates no additional CO_2 emissions, making them climate-neutral or zero-emission materials. However, it is worth noting that this climate-neutral classification may change over time, and it's challenging to predict which SCMs will become classified as the most environmentally friendly in the future. To compare the CO_2 emissions of different types of concrete, EPDs are used for each mixture. After analyzing the EPDs, contractors can categorize the concrete mixtures as Low Carbon A, Low Carbon B, Low Carbon Plus, or Low Carbon Extreme. Theses classifications are shown in the table 2.1 below.

Table 2.1: Limit values for low carbon concrete classification A, B, Plus, and Extreme according to module A1-A3 Smeplass et al. (2020)(own translation)

Strength class	**B20**	**B25**	**B30**	**B35**	**B45**	**B55**	**B65**
Maximum permitted greenhouse gas emissions kg CO_2-eq. per m^3 of concrete							
Industry reference	240	260	280	330	360	370	380
Low carbon class B	190	210	230	280	290	300	310
Low carbon class A	170	180	200	210	220	230	240
Low carbon class Plus	-	-	150	160	170	180	190
Low carbon class Extreme	-	-	110	120	130	140	150

The Industry reference values shown in the Table 2.1 are Norwegian generic values from 2019, used to estimate the reduction in CO_2 emissions when comparing different carbon classes. These values are regularly updated and should always be up to date when starting a new project. The following list gives a description of each class and how it is achieved. The literature source of this list is Smeplass et al. (2020).

- **Carbon class B** - is typically achieved with standard technical measures for concrete mixture design

- **Carbon class A**- Special prescription technical measures are needed. The targeted values for Low Carbon Class A are based on what is practically achievable in structural concrete made with common binders found in the Norwegian market today. It is possible to reach the targeted carbon class using conventional prescription methods by reducing the amount of binder in the concrete. One possibility is to use a larger amount of coarse aggregate to decrease the matrix volume of the concrete, as compositions with more fines/sand require additional binders.

- **Low carbon plus and extreme** The two strictest classifications can only be achieved by substituting significant amounts of Supplementary Cementitious Materials (SCMs), such as slag or fly ash, to reduce the cement content in the mixture, preferably in combination with silica dust. Contractors working within these strict carbon classes must have a clear understanding of the limitations given in the standards, including the K value, which indicates how much slag, fly ash, and silica dust can be substituted for cement in various strength and durability classes. In some instances, the use of these materials may not be permitted for specific strength and durability classes.

2.5 Supplementary Cementing Materials

The Supplementary Cementitious Materials (SCMs) market has increased significantly over the past thirty years due to increased demand for sustainable and eco-friendly construction practices. These materials are typically byproducts of industrial processes but can also be found Naturally. SCMs such as fly ash and silica fumes are often referred to as pozzolans and slag is often referred to as hydraulic cement. The name pozzolan is referring to volcanic ash mined in the Italian city of Pozzuoli roughly 2000 years ago (National Association of Home builders 2023).

- **Fly Ash -** Is the byproduct from a coal burning electrical power plant.
- **Silica fume -** or microsilica is manufactured from the reduction of high purity quartz with coal in an electric arc furnace. It's also a byproduct from ferrosilicon production Panesar (2019)
- **Slag -** is the byproduct frome iron making.

Table 2.2 shows the how these SCM's affect the mechanical properties of concrete. When reducing the amount of cement content by using SCM, it must be done in compliance with Standard Norge (2022). There are different parameters controlling the allowable ratio of binder which can be replaced for different types of SCM, and it varies for different durability classes.

This method is called the K-value method which is given in clause 5.2.5.2 (Standard Norge 2022). The mass ratio m between water and binder is given by

$$m = \frac{water}{binder} = \frac{w}{c + (k * p)} \tag{2.2}$$

where w is the total amount of free water, c is cement, k is the efficiency factor for a given additive used (i.e silica dust, fly ash and slag) and p is SCM. All variables are usually given in kg except k which is unitless. The efficiency factor k on which ratio the chosen SCM (pozzolan or hydralic binder) can replace parts of the Portland Cement (PC). In National Annex (NA) clause.5.2.5.2.2 the k-value for fly ash is equal to 0.4 or 0.7 depending on the durability class Smeplass et al. (2020). Adding additional pozzolan is only effective until the solution is saturated. Further additions of pozzolan is possible but it only works as filler and not as a binder. The k value is then set to 0.

Table 2.2: Table of properties for Fly Ash, Slag and Silica Fume showing some of effects these SCM have on the concrete properties. The difference between C and F ash is that they have high and low calcium contents respectively. Data from National Association of Home builders (2023).

	Fly Ash	**Slag**	**Silica Fume**
Specific Gravity	1.9 - 2.8	2.8 - 3.0	2.2 - 2.5
Typical addition rates as percentage of total cementitious materials	C Ash: 10% - 40% F Ash: 10% - 30%	20% - 50%	5% - 10%
Impact on setting times	C Ash: can retard or accelerate F Ash: typically retards	Typically retards but can accelerate	Generally retards
Impact on pumpability and finishability	Generally improves	Little effect	More difficult to finish, can improve pump-ability of a lean mix
Curing considerations	Similar to cement; normal curing methods	Similar to cement; normal curing methods	Reduces bleed water - requires immediate curing
Effect on strength gain	C Ash: can accelerate early F Ash: slow early, increased ultimate	Similar to normal concrete	Improved early and ultimate
Effect on impact and abrasion resistance	Some improvement - governed by compressive strength of mixture and aggregate types		
Effect on scaling resistance	Little impact - can be improved - governed by low w/c ratio and proper air entrainment system		
Effect on permeability and corrosion resistance	Improves	Improves	Greatly Improves
Effect on alkali aggregate reactivity	Improves - testing needed to veryify with local material availability		

2.5.1 Natural Supplementary cementitious Materials

If supplementary cementitious materials (SCM) is going to be a sustainable alternative for reducing cement content in the future, other alternatives to pozzolanic materials like fly ash has to be found as fly ash will not be available after the transition to renewable energy sources. Although substituting parts of cement clinker with fly ash is a good solution for waste management, the availability of this waste will most likely be reduced in the future. It's is also challenging to know if fly ash will be regarded as carbon-neutral in the future simply because it is a byproduct and not the main product being produced Smeplass et al. (2020).

To achieve sustainability for the use of SCM, it's therefore crucial to start the shift towards natural pozzolanic materials found in nature. By doing so, it's still possible to reduce cement content and prevent pollution from coal power plants while reducing costs and CO_2 emissions at the same time, especially when carbon taxes increase. Natural pozzolan is also considered carbon-neutral, with the key difference being that they are not produced as they are a natural resource. For instance, volcanic ash and pumice found in Iceland has been identified as a potential replacement when the number of coal power plants are reduced or eliminated completely EP Power Minerals GmbH (2023).

These natural pozzolans can offer a sustainable alternative for reducing clinker content in cement without relying on byproducts from other harmful industries. A potential solution for moving to a carbon neutral industry may therefore be to incorporate technologies like carbon capture and/or using natural pozzolanic materials.

2.6 Carbon capture methods

To reach the goal of zero emissions in the cement production industry, carbon capture techniques to capture the CO_2 that cannot be avoided during production is required. This includes CO_2 generated during the heating of the kiln and the chemical reaction that occurs when clinker is produced. In this section, three different approaches are presented: Carbon Capture (CC), Carbon Capture and Storage (CCS) in subsection 2.7, and Carbon Capture and Utilization (CCU) in subsection 2.8.

There are various methods that can be used for Carbon capture in cement production and in this section some of the techniques that are currently in use are presented. Although the different techniques have advantages and disadvantages, they all require electrical energy. Countries like Norway which have access to green energy from water turbines, can use more energy in this process, making it a beneficial for the environment even with high energy consumption when neglecting the economic aspect.

However, in locations where energy is generated using coal, natural gas, and fossil fuels, which are costly, it is critical to minimize energy consumption to ensure the sustainability of the process. The sum of CO_2 emissions from the energy produced must be less than what is captured from cement production for it to be sustainable. Furthermore, the economic implications must also be taken into account to encourage companies to adopt carbon capture (CC) practices. One approach to achieving this is through the implementation of a carbon tax, which is a policy tool employed by governments to place a monetary value on carbon emissions. By increasing the cost of polluting, companies are motivated to reduce their carbon emissions and adopt more environmentally friendly practices. Carbon tax is explained further in section 2.9.

In the paper Anantharaman et al. (2018) where SINTEF Energy Research was the lead participant several carbon capture methods are compared. As a reference they are using a clinker burning line without carbon capture. Figure 2.2 displays a schematic of the plant. Raw materials undergo grinding and drying in the raw mill, using hot flue gas from the preheater. The gas and the resulting raw meal are then separated in a dust filter. The raw meal is sent to the preheater while the gas is released to the stack. In the preheater, hot flue gas from the calciner and rotary kiln heats the meal. The meal and gas are mixed for heat transfer and separated in cyclones. The raw meal enters the calciner, where most of the calcination occurs, as shown in the equation 2.3.

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2.3}$$

Approximately two-thirds of the cement plant's fuel is utilized in this stage to obtain the desired temperature of around 860 °C and drive the endothermal reaction. The raw meal is fed into the rotary kiln after passing through the calciner, where it undergoes a chemical transformation to become clinker. The remaining one-third of the cement plant's fuel is burned in the main burner, which is located at the opposite end of the kiln. The solid material is heated to a temperature of 1450 °C, while the gas phase can reach temperatures up to 2000 °C. As the raw material travels through the rotary kiln, it undergoes several intermediate phases before forming clinker. Once the clinker is formed, it is transported to a clinker cooler, where it is cooled using ambient air Anantharaman et al. (2018).

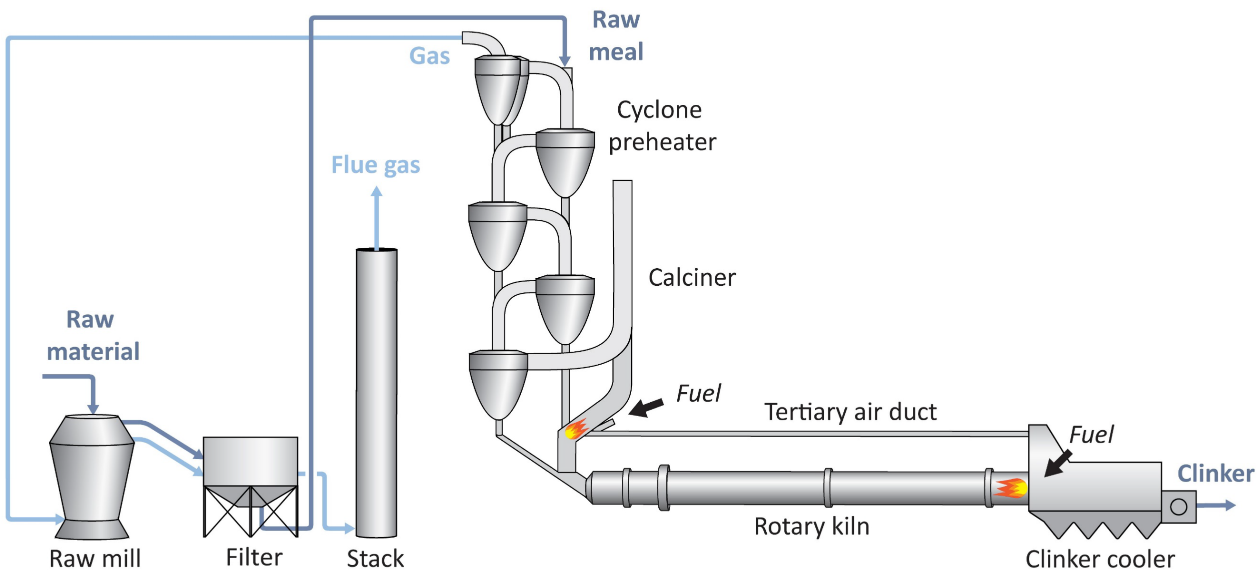

Figure 2.2: Reference cement plant without carbon capture (Anantharaman et al. 2018)

2.6.1 MEA – Adsorption

The use of steam in the MEA carbon capture process is the main factor contributing to both the increased primary energy consumption and the reduction in equivalent CO_2 emissions avoided. Specifically, steam usage has the greatest impact on the cost of CO_2 reduction in the MEA system shown in Figure 2.3, due to its role in significantly raising the cost of clinker production compared to the reference cement plant 2.2. Additionally, the generation of steam from natural gas results in a decrease in the amount of equivalent specific CO_2 emissions avoided Anantharaman et al. (2018).

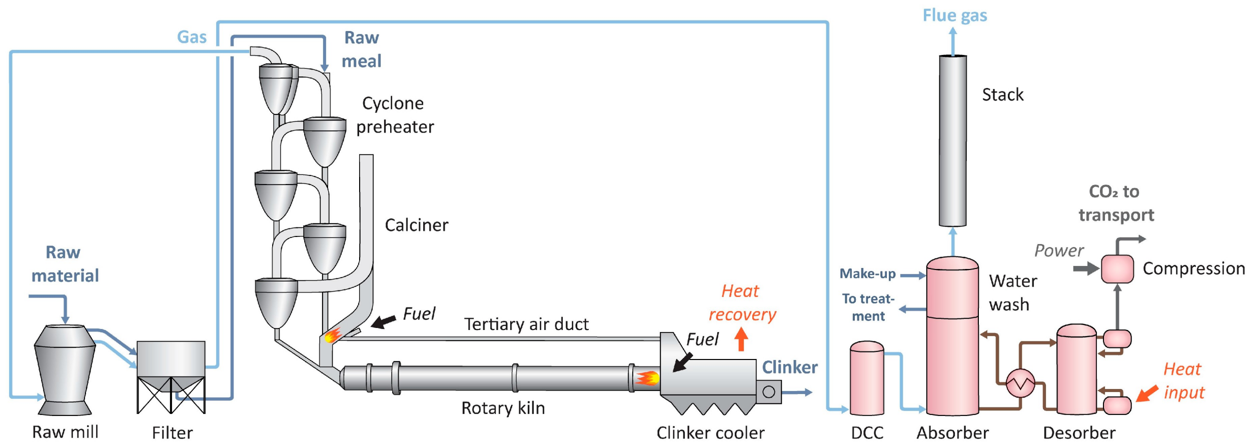

Figure 2.3: Cement plant with integrated MEA-Adsorption technology for carbon capture Anantharaman et al. (2018)

2.6.2 Calcium-Looping

The final Specific Primary energy consumption (SPECCA) value for both calcium looping processes depends on several factors including coal consumption, electric power consumption, and electric power generation. In particular, electric power generation is crucial for the tail-end technology depicted in figure 2.4 as it helps reduce the added equivalent specific primary energy consumption. The cost of CO_2 avoided is significantly affected by the increase in coal consumption and capital costs for both CaL technologies.

Both CaL methods produce a significant amount of electric power, with the tail-end process generating enough electricity to meet the capture process and a portion of the cement plant's demand. This results in a lower cost of electricity per ton clinker in the CaL tail-end process compared to the reference cement plant Anantharaman et al. (2018). The figures shown below illustrates both the tail-end configuration of Ca-lopping (2.4) and the integrated EF Ca-looping process (2.5).

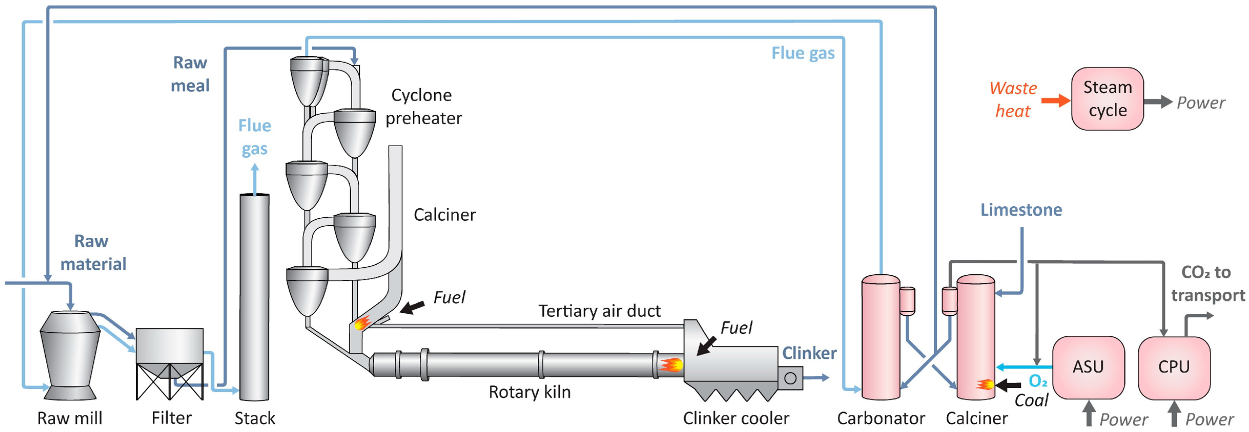

Figure 2.4: Cement plant with Calcium-Looping carbon capture technology at the tail end Anantharaman et al. (2018)

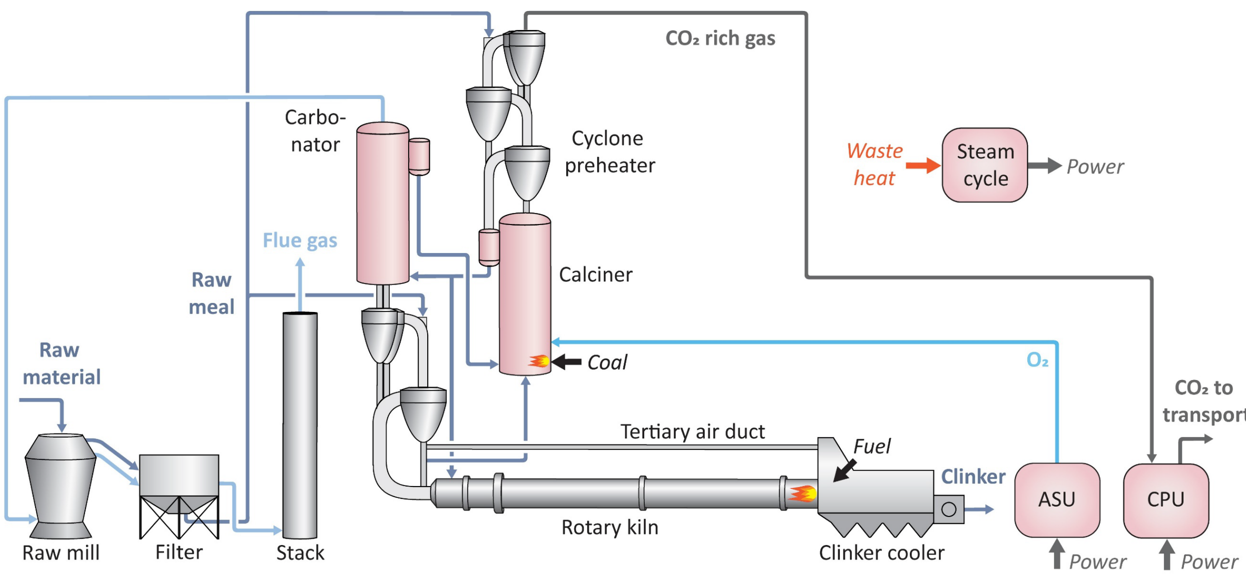

Figure 2.5: Cement plant with integrated Calcium-Looping carbon capture technology Anantharaman et al. (2018)

2.6.3 Oxyfuel- Process

The paper Anantharaman et al. (2018) indicates that among the technologies discussed, Oxyfuel has the lowest energy consumption. It's important to note that the electric power consumption accounts for nearly all of the energy needed by this technology and for the reduction in equivalent CO_2 emissions. The CPU is the main power consumer, followed by the ASU and the fans. The electrical power is generated from waste heat which reduces the net power consumption by almost 20%.

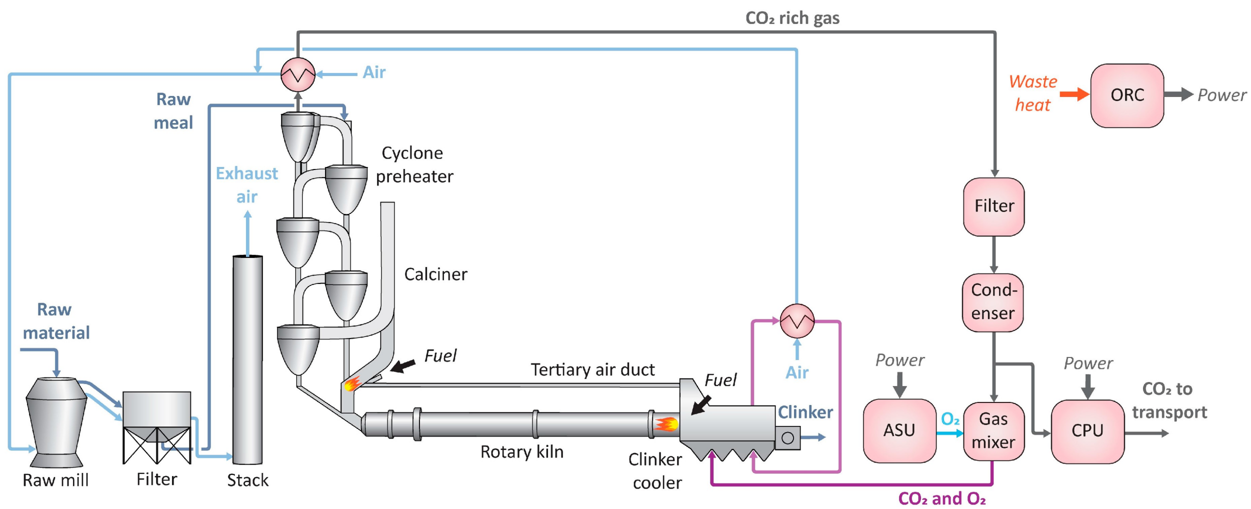

Figure 2.6: Cement plant with Oxyfuel carbon capture technology Anantharaman et al. (2018)

2.6.4 CAP

The chilled ammonia process is mostly reliant on steam consumption, which constitutes a significant portion of both primary energy consumption and reduction in equivalent CO_2 avoided. In fact, the steam consumption accounts for approximately 70 % of these values, whereas the electric power consumption contributes to the remaining portion Anantharaman et al. (2018).

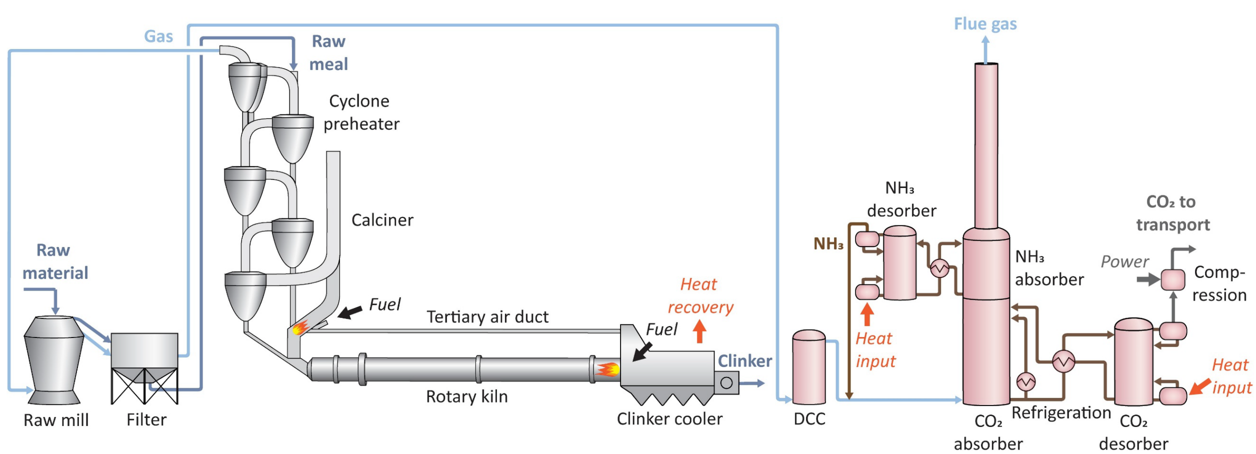

Figure 2.7: Cement plant with Chilled ammonia process (CAP) carbon capture technology Anantharaman et al. (2018)

2.6.5 Membrane

According to Anantharaman et al. (2018), the membrane-assisted CO_2 liquefaction process stands out as the only technology that exclusively uses electric power as its energy source. As a result, this process is associated with a reduction in equivalent CO_2 avoided emissions. Roughly 80% of this electric power consumption comes from the operation of the fan, pump, and compressor within the process, while the remainder is primarily due to the refrigeration system.

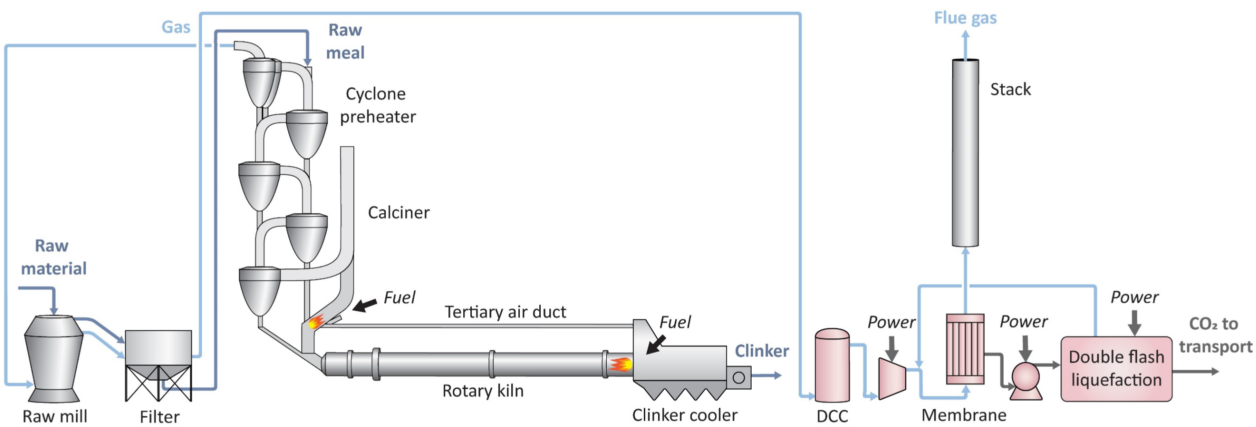

Figure 2.8: Cement plant with Membrane-assisted Co_2 liquification carbon capture technology Anantharaman et al. (2018)

2.6.6 Comparison of the different Carbon Capture technique's

When comparing the methods used in this paper Anantharaman et al. (2018), two methods stand out regarding power consumption: Oxyfuel with the lowest energy consumption per kg CO_2 and MEA with the highest energy consumption per kg CO_2, as shown in Figure 2.10. Table 2.9 illustrates the data used to calculate the specific energy consumption (SPECCA) for each method.

The steam consumption of MEA is the largest among the methods tested, and therefore the calculated CO_2 avoided is reduced in this comparison. Figure 2.9 shows a table with the data used to calculate the SPECCA value which is the energy consumption per kg CO_2 avoided for each of the methods. Regardless of the energy sources used, all carbon capture technologies have one common factor: a large increase in power consumption during clinker production as shown in figure 2.11. It is only through the implementation of carbon taxes that it will become economically beneficial for producers to invest in these technologies.

	MEA	Oxyfuel	CAP	MAL	CaL - tail-end	CaL – Integrated EF
Added equivalent specific primary energy consumption [MJ_{LHV}/t_{clk}]	**3959**	**1173**	**2401**	**2216**	**3280**	**2528**
Coal consumption	0	4	0	0	3859	2195
Steam consumption (NG boiler)	3073	0	1859	0	0	0
Electric power consumption	887	1351	542	2216	2086	1740
Electric power generation	0	-182	0	0	-2665	-1408
Equivalent specific CO_2 avoided [kg_{CO2}/t_{clk}]	**559**	**719**	**640**	**687**	**806**	**797**
At cement kiln stack	761	758	762	761	787	808
Steam consumption (NG boiler)	-172	0	-104	0	0	0
Electric power consumption	-30	-45	-18	-74	-70	-58
Electric power generation	0	6	0	0	89	47
SPECCA [$MJ_{LHV}/kgCO_2$]	**7.08**	**1.63**	**3.75**	**3.22**	**4.07**	**3.17**

Figure 2.9: Specific Primary energy consumption (SPECCA) comparison for all the carbon capture technology's. A lower SPECCA value means that the method uses less energy than other methods with a higher SPECCA number. Figure from Anantharaman et al. (2018).

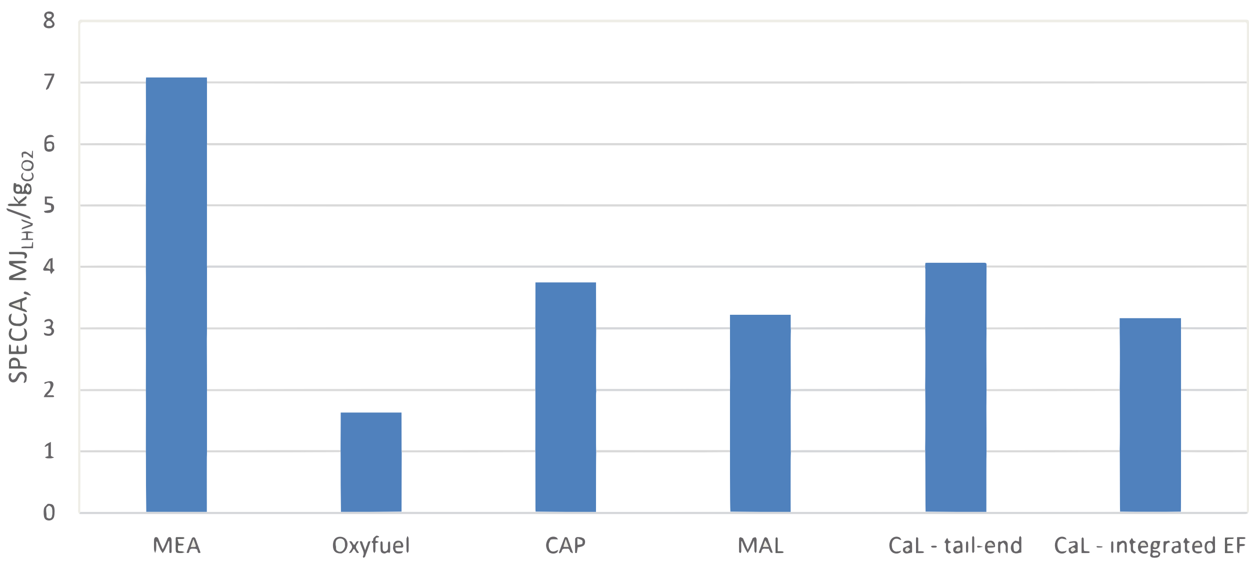

Figure 2.10: Comparison of energy consumption for the different methods of capturing Co_2 (SPECCA). Lower is better. Oxyfuel is the method which requires the least amount of energy to function. Figure from Anantharaman et al. (2018).

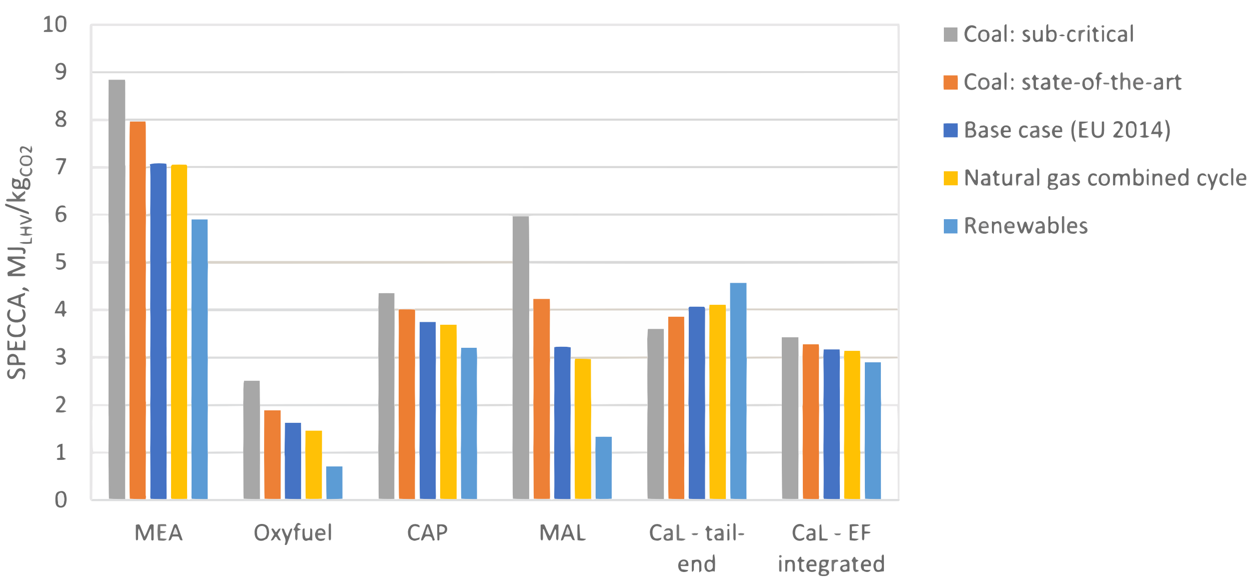

Figure 2.11: Comparison of the specific primary energy consumption for CO_2 avoided for the different carbon capture technologies with different cases of power generation. Figure from Anantharaman et al. (2018).

2.7 Carbon capture and storage (CCS)

To address the major environmental challenges present today, methods for carbon capture has been presented. First the gas is captured and then it needs to be transported, either by pipeline as a gas, or as liquid on pressurized tanks. This chapter focuses on exploring two storing methods. The first method has been used on Iceland since 2014 and is known as Carbfix and is presented in section 2.7.1. The second method have been used offshore by Equinor since 1996 and this technique utilizes depleted oil reservoirs for storage. This method is presented in section 2.7.2.

2.7.1 Carbfix

There are several ways to store captured CO_2, and one of the solutions is Carbfix. While trees and plants are known for removing carbon dioxide from the air, carbon can also be stored in rocks. According to Carbfix (2023a) this technology mimics and accelerates this natural process by dissolving carbon dioxide in water and exposing it to reactive rock formations like basalts. Carbon dioxide is dissolved in water and then injected into the subsurface, where it is converted into solid carbonated minerals through natural processes that take about two years.
Basalt is widely available and actually the most common type of rock on Earth. This makes it the ideal candidate for carbon storage because it has a high reactivity due to the presence of minerals such as calcium, magnesium, and iron-rich silicate. These minerals are needed to form carbonated minerals that store carbon dioxide. Basalt is also porous and contains a lot of cracks, providing a large internal volume available to permanently immobilize CO_2 in a mineralized state.
It has been estimated that just the basalt rocks in the active rift on Iceland could potentially store over 400 billion tons of CO_2, which is more than the amount of CO_2 produced by all of the world's fossil fuels combined Carbfix (2023d). The figure 2.12 shown below shows an illustration of the process, which also shows the amount of CO_2 that has been stored using this method in Iceland since its 2014.

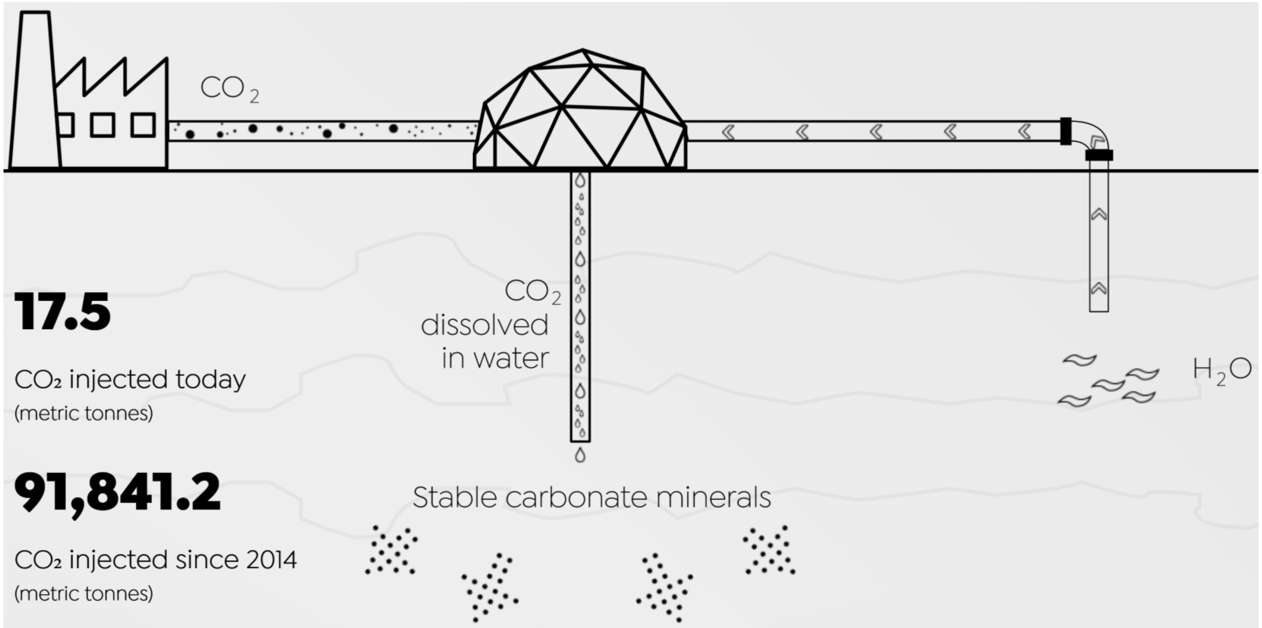

Figure 2.12: Carbfix Carbon storage solution, the figure illustrates how CO_2 gets dissolved in water and stored as carbonated minerals in reactive rock formations. Figure from Carbfix (2023c)

The Carbfix process requires a large amount of fresh water which limits the locations suitable for this method. However, Carbfix has started developing and testing a method to use sea water instead, which would make it accessible to even more people in coastal or offshore areas. This project is known as Project CO_2-SeaStone and is located at Reykjanes Peninsula in Iceland (Carbfix 2023b).

When carbonated water is pumped into geological formations it tends to sink because it is denser than the water present in the formation. This is different from traditional carbon capture and storage methods in oil and gas fields where the sealing cap rock above the reservoir/aquifer is preventing gaseous CO_2 from leaking to the surface(Carbfix 2023a). This could potentially make Carbfix's carbon storage solution a safer alternative, because the carbon is permanently sequestered into the rock and cannot escape back into the atmosphere as a gas. This solution may therefore be considered safer than simply injecting CO_2 into the formation as the risk of CO_2 escaping back through the wellbore is lower after the CO_2 has been mineralized.

2.7.2 Storing CO_2 in depleted oil and gas reservoirs

Another solution is to store the CO_2 in the large volumes which are present in water saturated formations and in depleted oil and gas fields. Equinor is a leading expert in this field, and have been storing CO_2 offshore since 1996 Overå, Sverre J (2023). The volumes should have sufficient porosity and permeability to store large enough volumes. A low permeability means a poor injectivity which is the rate at which CO_2 can be injected into the formation. In order for the CO_2 to not escape to the surface again it requires a cap rock. As mentioned in section 2.7.1 a cap rock is a impermeable seal that the CO_2 can not penetrate. A waterfilled sandstone formation below a shale layer (which acts as the cap rock) is an example of an excellent storage location for CO_2. Norwegian Petroleum Directorate (2023). According to Overå, Sverre J (2023) the CO_2 is held in place by different trapping mechanisms to ensure safe containment:

- **Structural trapping**: Sealing cap rock preventing the CO_2 to escape upwards.
- **Capillary/residual trapping**: Large part of the CO_2 is trapped and immobilized in pore throats between sand grains.
- **CO_2 Dissolution**: With time, the injected CO_2 will dissolve in the salt water in the reservoir and sink down.
- **Mineralization**: Some dissolved CO_2 will form mineral, thus becoming completely immobile.

2.8 Carbon capture and utilisation

The environmental challenges the world is facing today requires new intuitive solutions. CO_2 can not only be viewed as a problem, but also as a renewable resource that newer runs out. An example of this is Air Company which have recently developed a method called AIRMADE^{TM} (AIR COMPANY 2023a).

With this technology CO_2 gas can be used as a resource to produce Sustainable Aviation Fuels (SAF) and alcohols, with oxygen as the only byproduct. The goal of Air Company is to implement this technology to help reduce the emissions for industries globally. In areas where the distance to a suitable storage site is large the production of SAF is a promising solution if concrete production is built close to an airfield to further reduce the emissions associated with transportation. Air company has projected that if this technology is scaled globally, it could potentially avoid 10.8% of global CO_2 emissions. This would be the equivalent of preventing more than 4.6 billion tons of CO_2 from being released annually, which is more than three times the amount of CO_2 emissions produced by the entire African continent AIR COMPANY (2023b).

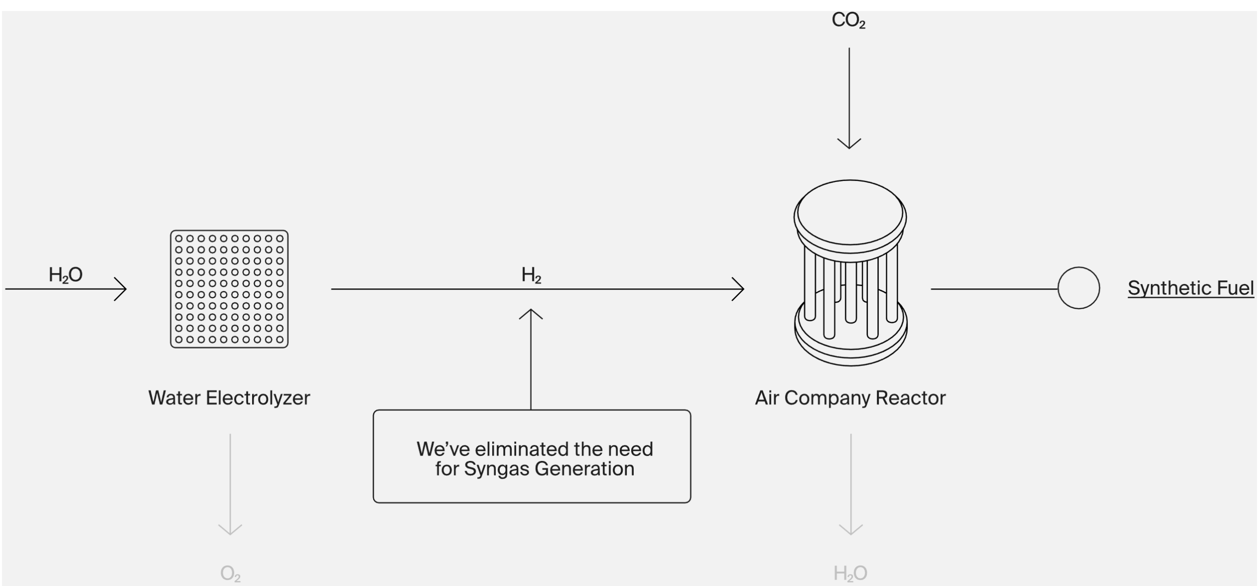

Figure 2.13: Overview of Air Company processing. H_2 gas and CO_2 is combined in the reactor to create synthetic fuel which can be used in the aviation industry. Figure from AIR COMPANY (2023a).

2.9 Carbon Tax

Carbon tax was recently introduced by the EU in order to drive faster development to achieve the climate goals by making it costly to pollute. Prices vary like a stock market, where it's possible to buy and sell the rights to have certain amounts of CO_2 emissions. The CO_2 price is influenced by the environment, weather, and wind. If it's very cold and windy, it will result in needing more energy from non-renewable energy sources to meet the demand. This in turn leads to increased prices for CO_2 emissions. The war in Ukraine and the end of gas deliveries from Russia have also led to a energy shortage in the EU, which was temporarily replaced by a 7% increase in coal burning power plants. These power plants that have approximately double the CO_2 emissions compared to the gas received from Russia. This has resulted in the price per ton of CO_2 being pushed up to a staggering 106.6 € per ton. However, carbon prices vary greatly globally, for example, China's price for the same period is 9.4 € as they are not part of the European market Abnett et al. (2023).

Illustrated below in figure 2.14 a comparison of clinker cost and cost of CO_2 avoide for the different carbon capture methods and the reference cement plant without carbon capture 2.2, with prices close to 50€, it will be profitable to use Oxyfuel technology due to the increasing carbon taxes in Europe. This tax forces the producer to adopt to a more carbon-neutral method, to remain competitive with other manufacturers.

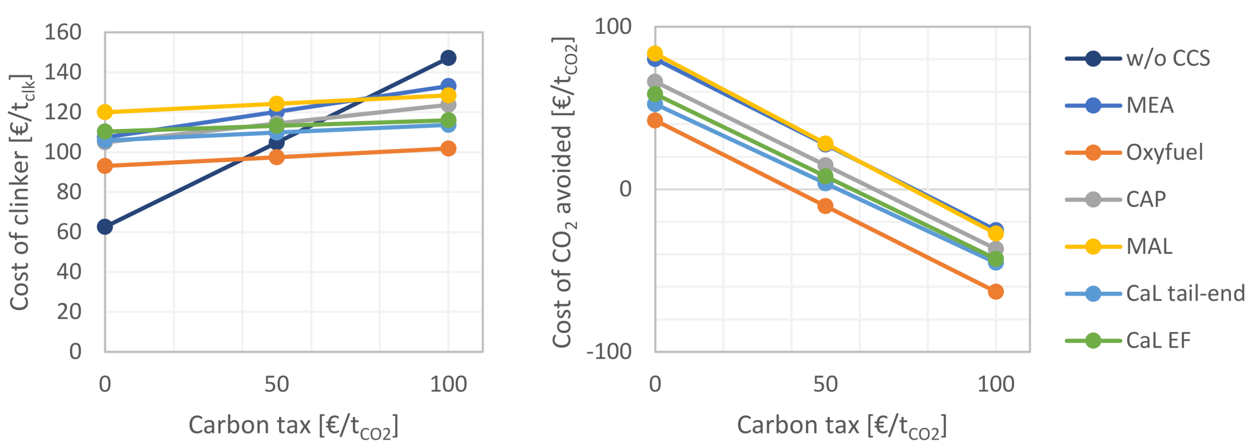

Figure 2.14: Carbon tax and cost of clinker. The left subfigure when the various carbon capture methods used in a clinker plant are profitable compared with a reference plant without CCS. The right subfigure shows the costs of CO_2 avoided when carbon taxes varies. Figure from Anantharaman et al. (2018).

2.10 Future of concrete

The Norwegian government is working on a project known as the "Longship" program which has the objective of demonstrating how carbon dioxide may be captured from sources related to industry and properly transported and stored into depleted oil and gas fields.
One of the projects that is included in this program is called Brevik CCS, and it is the most advanced CCS project that Heidelberg Materials has. An overview of the plant can be seen in figure 1.1. The facility is expected to be operational by the third quarter of 2024. When CCS technology is optimized, it can be implemented into other industries such as power plants based on coal or oil, or steel production Breivik,CCS (2023). The aim of Brevik CCS is to capture and store 50% of the plant's emissions, equivalent to 400,000 tons annually.Halvorsrud,Tor (2023)

Based on their successful collaboration with the Norwegian government and their investment in the technology, they have chosen to raise their ambitions for a new state of the art carbon capture installation in Sweden Webb,Comstedt,Karin (2023). Heidelberg Materials announced in 2021 that they are planning to build the world's first carbon-neutral cement plant. The project aims to capture up to 1.8 million tonnes of carbon dioxide annually Fairs,Marcus (2023).

When carbon dioxide is captured by plants through photosynthesis or from CCS process from the industry as mentioned in section 2.8, it can be combined with hydrogen to create for example aviation fuels as shown in figure 2.13. Fuels like this are considered carbon-neutral, since the CO_2 was captured, hence avoided and then utilized as fuel. In the project in Sweden, they aim to capture emissions from biomass fuels as well, making them carbon negative.

2.10.1 Geopolymer concrete

Geopolymer concrete is a type of concrete where the commonly known Portland cement binder is replaced by Aluminosilicate precursor and water is replaced by an alkali-activator. The difference is shown in equations 2.4 and 2.5:

$$\text{Normal concrete} = \text{Portland cement} + \text{Water} + \text{Aggregates} \tag{2.4}$$

$$\text{Geopolymer concrete} = \text{Aluminosilicate precursor} + \text{Activator} + \text{Aggregates} \tag{2.5}$$

From the equations, one of the main differences is that when Geopolymer concrete is used, pure water is not used as the activator. This is because the chemical reaction is sensitive to the mixing ratio. Instead of water, a $NaOH$ or KOH solution is diluted in water and used to initiate the hydration process.

Geopolymer is considered to have less of an impact to the environment as it uses byproducts from mining which are considered waste. This is further elaborated in the next section. Table 2.3 gives a summary of the reaction mechanism of geopolymer and other properties of the two cement types. This summary is derived from a guest lecture by Torbjørn Vrålstad which works at Saferock. The lecture was held in the autumn of 2022 at UiS Vrålstad, Torbjørn (2022).

Table 2.3: Portland and Geopolymer cement comparison. Note the difference in pH levels, strength development and durability. Data summarized from a guest lecture held by Vrålstad, Torbjørn (2022).

Difference of Ordinary Portland Cement and Geopolymer		
Cement	Portland	Geopolymer
Reaction mechanism	Hydration (Reaction between cement powder and water)	Dissolution (of precursor) Precipitation of geopolymer
pH	12-13	14-15
Ca-content	High	Low
Strength development	Fast	Slower (i.e less fast)
Long-term strength	Similar expected	
Durability	High	Expected to be better, especially in acid environments and at high temperatures

There are several challenges when developing Geopolymer cements, and workability is one of them. The previous admixtures such as Superplasticizer are developed for Portland cement, so new admixtures need to be developed that can work together with geopolymer cement. Another challenge is that the standards used to ensure the quality of our buildings are all based on Portland cement. This makes it very challenging to transition to something new that may be better for the environment. Since this type of cement does not use water as an activator, it creates problems when used in rainy weather, for example.

However, there are still many areas of application where it's possible to explore the use of this type of cement. One such area is in the construction of wind turbine parks and their floating foundations, as it is expected to be more resistant to acidic environments this could be a sustainable solution.

Alternatively, non-load-bearing parts of buildings, such as slabs, could be replaced with this type of cement, as it could be casted indoors. This way, there will be no issues with exposure to water, and it will not pose a serious risk if it does not function as expected. This could help the transition towards geopolymer as sustanable solution for the future Vrålstad, Torbjørn (2022).

2.10.2 Saferock

Saferock, a leading developer of geopolymer concrete located in Norway, has received support from Equinor Ventures with the development of a geopolymer cement based on the byproducts from Titania‘s mine located in Sokndal(Equinor ASA, 2022).

Saferock began in 2012 at the University of Stavanger, as part of a research project supported by Aker BP and Total, with a budget of 6 million Norwegian kroner. The scope of the project was to develop cement for sealing oil wells. The project was a success with promising results which resulted in the technology being patented by PhD student Mahmoud Khalifeh. This patent laid the foundation for Saferocks' investment in geopolymer concrete as a alternative for the widely recognized Portland cement.

Although sealing of oil wells does not involve the largest volumes, it was a good starting point for the development of such a product. This is because comparable products based on Portland cement must meet the oil industry's strict requirements for quality and durability. In fact, one of the best quality-assured types of Portland cement is well cement, according to valide (2023).

Saferock's new scope is to adapt this technology to a much larger sector, the construction industry. In this industry such a product could have a significant environmental impact with lower CO_2 emissions compared to Portland cement, according to valide (2023).
They also note that the price will be somewhat higher than that of Portland cement; however, because of the reduction in CO_2 emissions, it is expected that the costs will be similar when carbon tax is implemented, as was discussed in section 2.9. In addition to what was mentioned earlier, Validé states that Norcem's and Heidelberg's projects, with the aim to reduce CO_2 emissions from concrete production by 50%, have a price point of 17 billion Norwegian kroner. Validé believes they could be able to achieve the same result with a 1 billion kroner investment (valide 2023).

Chapter 3

Research Methodology

This chapter focuses on comparing the CO_2 emissions between Saferock's geopolymer cement and Schenker's low-heat cement by performing environmental impact calculations. The cultural center used for the calculations consists of three floors in total: a cinema on the first floor, a library on the second floor and a museum on the third floor. Each floor is designed to be 1500 m^2 giving a total area of 4500 m^2. The reference for this analysis will be the available EPDs (Environmental Product Declarations) published by EPD-Norge.

First, the strength and durability requirements of the concrete is presented. The required volume, transportation and pumping for each type of concrete including CO_2 emissions is then estimated. Both cement types will use the same mix design in equal quantities.

3.1 Strength and durability classes

The chosen concrete quality is strength class B35, with a durability class of M60. This is chosen because B35 is the first strength class Saferock will develop according to Seehusen, Joachim (2021). The mix design for the concrete is obtained from Trønderbetong AS, (2020) available at EPD Norway's website and it provides the mixing ratios of the different components. This is shown in Table 3.1.

A strength class of B35 indicates that the concrete must possess a minimum compressive strength of 35 N/mm² (35 MPa) to meet the required standards. The ratio between water and cement is the primary factor influencing the final strength and in this mixture the water/cement ratio is equal to 0.47.

The durability class M60 defines the concrete's ability to withstand specific environmental conditions. The durability classes range from M90 to MF40. When the "F" is included it means that the concrete needs frost resistance if it's exposed to rain and freezing. Each class corresponds to different environmental exposures, which is needed to determine the necessary cover of the reinforcement to prevent corrosion of the reinforcement during the lifetime of the structure (Epd-norge 2023). Table 3.2 gives information about the concrete exposure class and different durability classes is presented to get a clear overview.

Table 3.1: Concrete prescription B35 M60 Trønderbetong (2023)

Material	**Weight %**
Cement	14.34
Aggregate	78.87
Water	6,69
Chemicals	0.11

Table 3.2: Information about Exposure Classes and Durability classes taken from tables included in Standard Norge (2022).

Exposure Class	Durabillity class					
	M90	**M60**	M45	MF45	M40	MF40
X0	x	**x**	x	x	x	x
XC1, XC2, XC3, XC4, XF1		**x**	x	x	x	x
XD1, XS1, XA1, XA2[a],XA4[b]			x	x	x	x
XF2, XF3, XF4				x		x
XD2, XD3, XS2, XS3, XA3[a]					x	x

Exposure Class	Description of the environment.	Examples of where the exposure classes can occur (informative).
No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: All exposures except where there is freeze/thaw, abrasion or chemical attack. For concrete with reinforcement or embedded metal: Very dry	Concrete inside buildings with low air humidity
Corrosion induced by carbonation		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity; Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact; Many foundations.
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity; External Concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
Freeze/thaw attack with or without de-icing agents		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing

3.2 Concrete Volume

In this section, the amount of concrete required is estimated. Hollow-core slabs from Spenncon is used to reduce the amount of cement required which in turn reduces the CO_2 emissions. The support structure for the hollow-core slab is made of steel, as illustrated in Figure 3.1, and is therefore not included in the volume calculation.
The dimensions of the hollow-core slab is determined by utilizing Spenncon's hollow-core graph in figure 3.2. Using this graph requires knowing the span length and the applied load.
The span length is chosen to be 16.7 meters and the applied load is calculated by

$$\text{Applied load} = p + 0.8 * g = 5.0 + 0.8 * 0.5 = 5.4 \text{ KN/m}^2 \tag{3.1}$$

where p is the imposed loads class C5 and is equal to 5.0 KN/m^2 in accordance with values given in table NA.6.2 from NS-EN 1991-1-1:2002+NA:2019 (Standard Norge 2019), the 0.8 is a constant in the formula provided by Spenncon's dimensioning table shown in A.2 (assumed to be reserve capacity) and g is the slab which is equal to 0.5 KN/m^2.
Since this calculation is only used to estimate a concrete volume only the characteristic load is calculated since design load is assumed to not be required. During design of buildings this should always be calculated. This determines that the required hollowcore needed is HD400. A schematic of this hollow core is shown in appendix A.1.
The total concrete volume is estimated to be 3022.7 m^3. Calculations and a result summary is shown in the table 3.3. This does not include internal non-bearing walls and leveling compound for floors and finish, it is rather a rough estimation of how much concrete is needed to make the building structure which carries the load. Note that the concrete volume of the walls are multiplied with 0.9 in order to compensate for the volume reduction due to windows and doors.

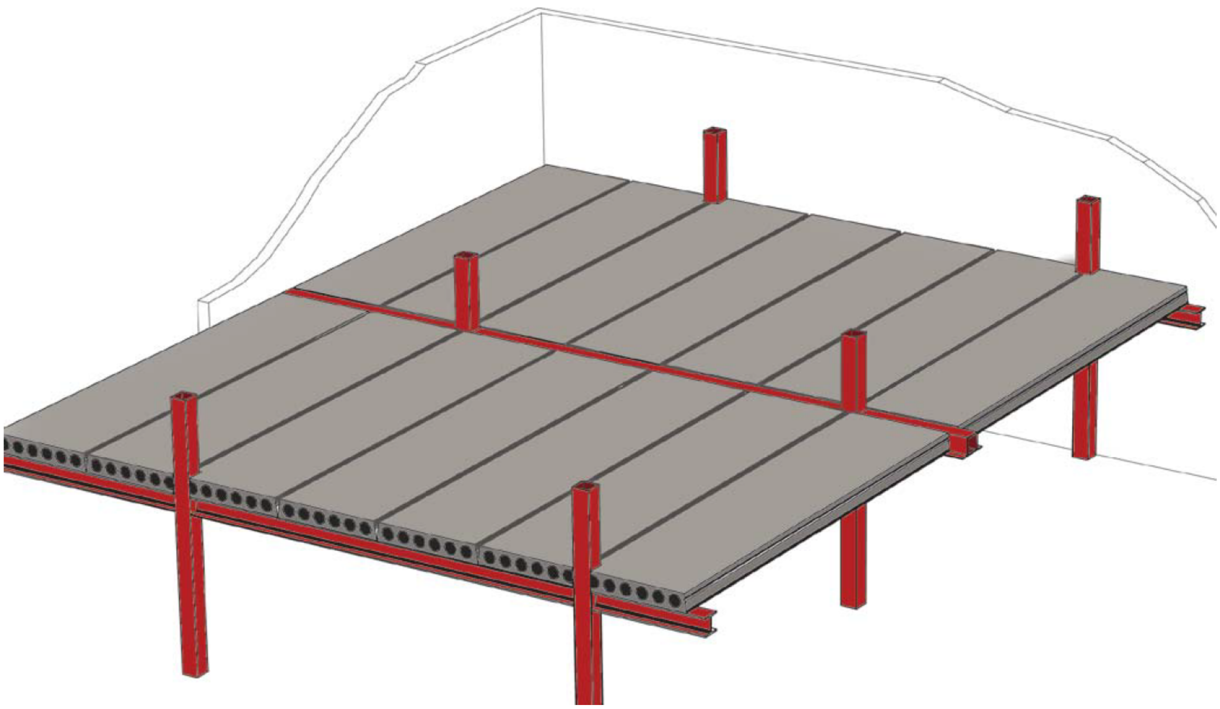

Figure 3.1: Steel Support structure for hollow slab. Figure from (Nesje, Arne and Krokstrand H, Ole 2023)

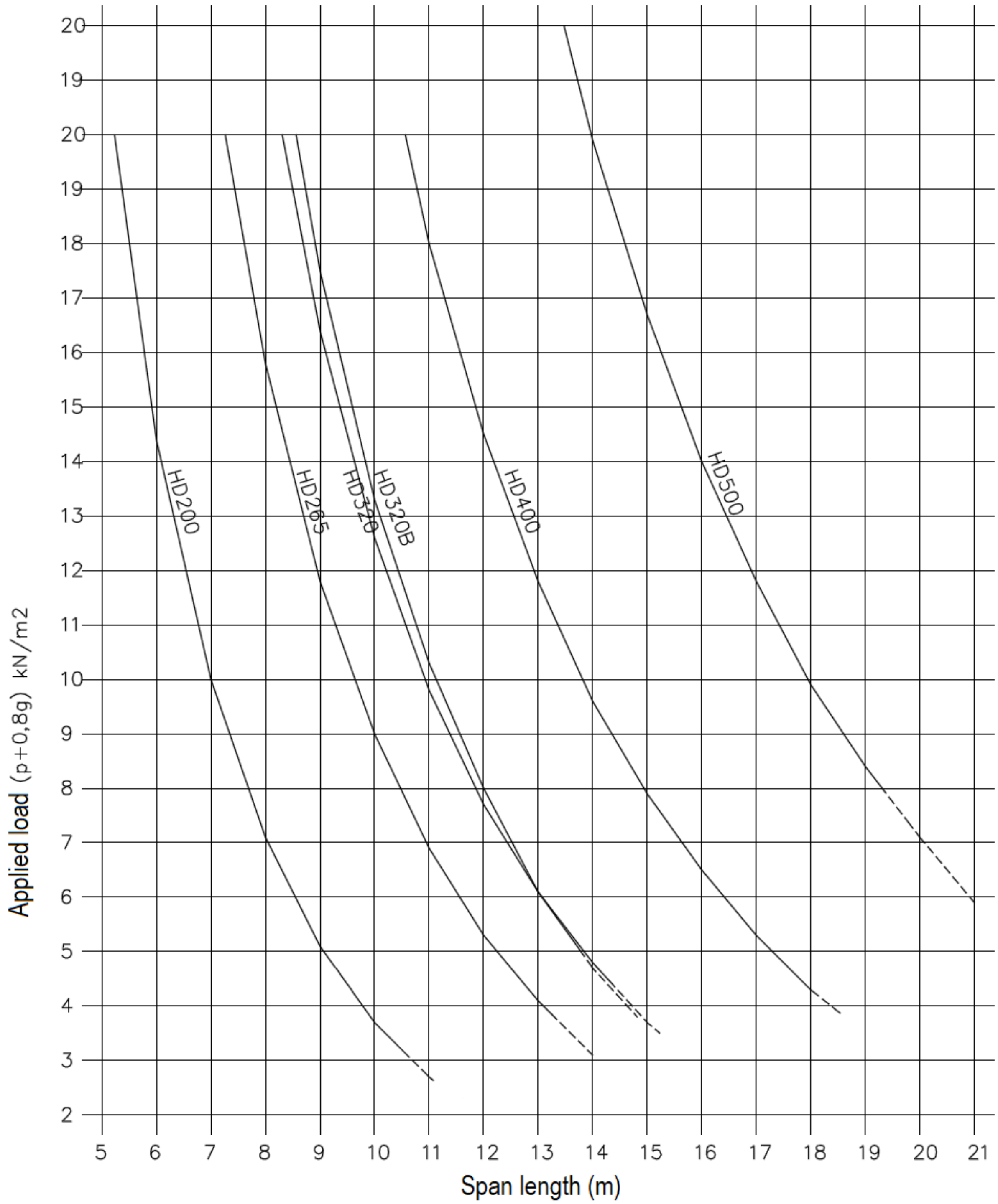

Figure 3.2: Dimensioning diagram for hollow core slabs. The span length is 16.7 meters and the applied load is 5.4 KN/m^2. This results in selecting HD400 as a suitable cross section. Figure modified from Spenncon AS, (2011) and the original page is available in Appendix A.2.

Table 3.3: Summary table of concrete and reinforcement estimation

Area		**Unit**
Total Area	4500	m^2
Each floor	1500	m^2
Number of floors	3	
First floor slab		
Area	1500	m^2
Thickness	0.150	m
Volume = (Area * Thickness)	**225**	**m^3**
Hallowcore HD 400 (Second floor, third floor and roof)		
Length	16.7	m
Width	1.2	m
C/S Area	0.2157	m^2
Volume of one Hollowsection = (Length * C/S Area)	3.6	m^3
Hollowsections each floor, = (Floor Area) / (Length*width) of Hollowsection	75	
Total Hollow sections (second floor, third floor and Roof) = Hollowsections each floor *3	225	
Total volume for Hollowsection = Volume of one Hollowsection * Total hollow sections	**810**	**m^3**
Walls		
L1 = Width of building	33.8	m
L2 = Length of building	44.4	m
Height	31.2	m
Thickness	0.3	m
Total volume for walls = ((L1) + (L2))*2*Height*Thickness*0.9 (windows and doors)	**1317.5**	**m^3**
Fundation Wall		
Length =(L1+L2) * 2	156.4	m
C/S Area	4	m^2
Total Volume = Length * C/S Area	**625.6**	**m^3**
Fundation Column		
Number of Columns	33	
Volume = (1.5 x 1.5 x 0.6)	1.35	m^3
Total volume = Number of columns * Volume	**44.6**	**m^3**
Sum		
Total Concrete Volume required	**3022.7**	**m^3**
Weigth of concrete = (Total concrete volume required * Density (2400kg/m^3))	**7254480**	**kg**
Weight of Reinforcement = (Total Concrete volume required * Density 100kg/m^3)	**302270**	**kg**
Weight of concrete	**7254.48**	**ton**
Weight Reinforcement	**302.27**	**ton**

3.3 Epd‘s

The environmental calulations are based on available EPDs published by EPD Norway. For several of the EPD's CO_2 emissions related to the transport of required materials to a mixing plant in Bergen is added. This is done in order to get a better estimation between the different concrete types as not all EPD's include a transportation range that cover a round trip to Bergen.
It is assumed that the same mixing plant can deliver geopolymer concrete, hollow core slabs and concrete produced with Schwenk's low-heat cement. Both types of concrete have the same mixing ratios and the same amount of reinforcement.
It's also assumed that the same amount of binder is used in Schwenk's low-heat concrete as mining waste used as a binder in Saferock's geopolymer concrete. Another assumption is that the amount of water in the low-heat concrete is equivalent to the amount of activator used in Saferock's concrete, where the activator is a mixture of water and a given number of moles of NaOH.
The following life cycles are included in the calculations:

- **A1** - Raw material
- **A2** - Transport
- **A3** - Manufacturing
- **A4** - Transport to market

3.3.1 Schwenk low-heat cement

Table 3.4 shows the material composition of Scwhenk's low heat cement. In this type of cement huge quantities of SCM's are used to reduce clinker content which is the main contributor to CO_2 emissions when producing cement. In the table 3.5 the data which is used to calculate transportation from Bernburg to Oslo is included. To include the transport from Oslo to Bergen 5,5kg CO_2 is added for each ton of cement transported according to the EPD published by SCHWENK Norge AS (2023).

Table 3.4: Material composition of SCHWENK Lavvarmesement, Cem III/B 42,5 L-LH/SR (na) (SCHWENK Norge AS 2023). Note that SCM is 64.09% of the total weight.

Materials	kg	%
Additives	20,40	1,81
Aggregate	40,77	3,62
Raw materials, Mineral	343,04	30,48
SCM	721,27	64,09
Total	1125,47	

Table 3.5: Transportation from Bernburg, Germany to Oslo, Norway. The EPD includes return to Germany and this is why capacity utilization is 50%. Data from SCHWENK Norge AS (2023), relevant page is available in Appendix A.3.

Transport to market	Capacity utilisation (incl. return) %	Distance (km)	Fuel/Energy	Unit	Value (Liter/ton)
Train, Diesel	50,0 %	340	0,013	l/tkm	4,42
Ship, Cement boat	50,0 %	682	0,013	l/tkm	3,41

Table 3.6: Total global warming potential in kg CO_2-eq including transportation to Bergen, data from SCHWENK Norge AS (2023). Relevant page is available in Appendix A.3.

Parameter	Unit	A1	A2	A3	A4
GWP(Global warming potentila) - Total	kg CO_2 -eq	1,05E+00	8,33E+00	2,13E+02	2,97E+01
Sum	**kg CO_2 -eq**		**252.08 + 5.5 = 257.58**		

3.3.2 Reinforcement

Table 3.3 shows that the concrete volume required is 3022.7 m^3. The amount of reinforcement required is estimated to be 100kg/m^3 and this results in 302.27 tons of reinforcement. The calculations are shown in table 3.3. In the Norwegian Steel EPD Norsk Stål AS, (2021) for reinforcement steel 64 km transportation is included as an average to customers from the Norwegian Steel supplier including return.

One of the locations of Norwegian Steel is at laksevåg in Bergen. No additional km for transportation is therefore added as 64 km should be sufficient for a building located in Bergen.

Table 3.7: Total global warming potential for 1 ton of reinforcement steel including transportation. Data from Norsk Stål AS, (2021). Relevant page is available in Appendix A.7.

Parameter	Unit	A1-A3	A4
GWP (Global warming potential)	Kg CO_2 - eqv	3.93E-01	1.02E-02
Sum per kg	**Kg CO_2 - eqv**	**0.4032**	
Sum per ton	**Kg CO_2 - eqv**	**403.2**	

3.3.3 Aggregates

The life cycle categories included in the aggregates delivered by Forsand Sandkompani is A1-A4. In the A4 category (transport to customer) the company included 125km transportation by boat including return in the EPD Haukalid , Rune (2021). The distance to Bergen from Forsand Sandkompani is approximately 250 km. the values shown in the A4 category in table 3.8 is multiplied by 4 to get an estimation of 250km delivery to Bergen and 250 km return to Forsand Sandkompani.

Table 3.8: Declared 1 ton of aggregates ranging from 0-22mm fractions including delivery to Bergen by Boat. Transportation data is multiplied by 4 to cover the distance to Bergen and back from Forsand Sandkompani. Data from Haukalid , Rune (2021).

Parameter	Unit	A1-A3	A4
GWP (Global warming potential)	Kg CO_2 - eqv	1.88E+00	4 * (1.41E+00)
Sum	**Kg CO_2 - eqv**	**7.52**	

3.3.4 Mapei SX-N

Mapei SX-N is a superplasticizer which provides improved dispersion of the particles in the concrete. This results in a increased flow at lower water content. This is crucial for the workability and compactability in high strength concrete with low water content. It is assumed that the same amount of superplastizicer is used in both concrete types and that Saferock's geopolymere concrete is compatible.

Mapei's facility is located 530 km from Bergen, close to Oslo. The Epd Mapei Norge AS, (2021) does not include category A4 transportation to market. Transport estimates provided by the EPD made from the Swhwenk's low heat cement is therefore used instead. It states that 5.5kg of

CO_2 should be added for each ton of cement transported from Oslo to Bergen. 5.5kg of CO_2 per ton is therefore added to the superplasticizer global warming potential. In table 3.9 below the declared units in the EPD was only for 1 kg not 1000kg like the other EPD's. The CO_2 equivalent for transportation per kg is then 0.0055 kg.

Table 3.9: Total global warming potential for Mapei SX-N superplasticizer values are for 1 kg declared unit including transportation to Bergen. Data from Mapei Norge AS, (2021).

Parameter	Unit	A1-A3	A4
GWP (Global warming potential)	Kg CO_2 - eqv	5.31E-01	5.5E-3
Sum per kg	**Kg CO_2 - eqv**	**0.5365**	
Sum per ton	**Kg CO_2 - eqv**	**536.5**	

3.4 Saferock's activator and cement

As mentioned in subsection 2.4, fly ash is carbon-neutral since it is a byproduct of coal burning power plants. Similarly, the mining waste used in Safe rock's alkali-activated cement is also carbon-neutral. It is the titanium-rich minerals ilmenite, found in the rock types Norite and Anorthosite, that replace the commonly known Portland cement as the binder in Safe Rock's alkali-activated cement.

There are two main factors contributing to CO_2 emissions in this cement: the production of the two most commonly used activators (KOH or NAOH), and the energy required for grinding the alkali cement binder to less than 63 µm to make the substance more reactive. Seehusen, Joachim (2021) When the ilmenite is crushed into smaller particles, the surface area that gets direct contact with the activators is multiplied. Since this binder is produced in Norway the CO_2 emissions from the grinding process are excluded because it is assumed to be produced using renewable energy sources.

Emissions from transportation of the geopolymer cement to Bergen is included as well as the production of the activator NaOH (Sodium Hydroxide). Saferock's alkali-activated cement is extracted from Titania. The distance between Titania and Bergen is approximately 300 km. It's assumed that the CO_2 emissions from transportation are roughly the same as Schwenk's low heat cement which were 5.5 kg CO_2 per ton of cement. Scwhenk's estimate is using a distance from

Oslo to Bergen which is approximately 460km. By interpolation this results in $300 * (5.5/460) = 3.59$kg CO_2 per ton alkali activated cement transported to Bergen.

Table 3.10: Total Global warming potential in kg CO_2 -eq including transportation to Bergen from Titania for Saferock's binder per 1000kg. This estimate is interpolated based on transport emission data from Schwenk's EPD SCHWENK Norge AS (2023).

Parameter	Unit	A1-A3	A4
GWP(global warming potential)	kg co2 -eqv	0	3.59
Sum	**kg co2 -eqv**	**3.59**	

According to Saferock the activator used is not 100% NaOH (Sodium hydoxide) or Potassium hydroxide (KOH). They are not able to share details on which of the activators is the most successful or how much is needed, it's therefore assumed a concentration of 30-40% NaOH is used since this is the only EPD available on EPD Norge Borregaard AS, (2021). This means that 1000 kg of activator is equal to 35 % of the 345kg CO_2 per ton of NaOH since it's deluded in water. The calculation of CO_2 per ton activator is then 345 kg * 0.35 = 120.75 Kg Co_2 per 1000 kg activator.

Table 3.11: Total global warming potential in kg CO2-eq including transportation to Bergen the declared unit is 1000kg of sodium hydroxide. Data from Borregaard AS, (2021), relevant page available in Appendix A.6.

Parameter	Unit	A1-A3	A4	A1-A4
GWP(Global warming potential) - Total	Kg Co2 -eqv	7.00E+01	2.75E+02	3.45E+02
Sum	**kg Co2 -eqv**		**345**	

According to Brekke, Simon (2022), global delivery of KOH would produce 2.69 kg CO_2 eq per kg KOH, and the European version would produce 2.23 kg CO_2 eq per kg KOH. This would result in 223 kg CO_2 per ton KOH. If the same amount were used this would result in 223 kg * 0.35 = 78.05 kg per 1000kg activator. The reduction in emissions by using KOH compared to NaOH can then be calculated:

- Reduction = (120.75 - 78.05) = 42.7
- Percentage reduction = (Reduction / 120.75) * 100
- Percentage reduction = 35.36%

If KOH were used instead of NaOH it could reduce the CO_2 emissions for the activator by approximately 35.36%. Most of the emissions from NaoH comes from the transportation category A4 where 1000km is included in the EPD.

Chapter 4

Results and Discussion

In this chapter the results from the calculations are presented and discussed. First the two concrete types with life cycle categories ranging from A1-A3 are presented and these values are compared with the limiting values for low carbon concrete classification given in table 2.1. The values in that table is also limited to life cycle categories A1-A3. After this transportation and reinforcement is included to give a comprehensive view of the total emissions.

4.1 Concrete A1-A3

In the first case all the materials in the concrete is transported to Bergen from supplier to a mixing plant located in Bergen. This comparison shows that Scwhenk's Low heat concrete has the highest kg CO_2 / m^3 at 104.3 compared to the Saferock's 36.27 Kg CO_2 / m^3 shown in table 4.1. This is equal to a 65.23% reduction of kg CO_2 / m^3. When comparing the data in table 2.1 to obtain the carbon class of the two concrete mixtures with a strength class of B35, both alternatives are able to meet the strict requirements of low carbon class extreme. This carbon class is the strictest classification available which have a maximum permitted greenhouse gas emissions of 120 kg CO_2 eq per m^3.

- Reduction = (104.3 - 36.27) = 68.03
- Percentage reduction = (Reduction / 104.3) * 100
- Percentage reduction =(68.03 / 104.3) * 100 = 65.23 %

Ton CO_2 reduced by using Saferock's cement alternative = (315.27 - 109.65) = 205.62 Ton CO_2. Using Saferock's cement a reduction of 65.23 % in CO_2 emissions is achieved.

Calculating how much of the emissions comes from the activator used in Saferock's geopolymer concrete:

- Total emissions from activator:

  = Weight [ton] * Kg CO_2 per ton * 1/1000 = 485.325*120.75*1/1000 = 58.6ton CO_2

- Pecentage of emissions from the activator = emissions from activator/total emissions

  = (58.6/109.65)*100 = 53.45

Table 4.1: Calculation of global warming potential in kg CO_2 equivalent for life cycle A1-A3

Scwhenk - Lowheat concrete Volume = 3022.7 m^3 (A1-A3)			
	%	**Weight [ton]**	**Kg CO_2 per ton**
Total	100	7254.48	
Cement	14.34	1040.292	257.58
Aggregate	78.87	5721.608	7.52
Water	6.69	485.325	0
Superplasticizer	0.11	7.97992	536.5
Calculation : Weight [ton] * Kg CO_2 per ton = Cement + Aggregate + Water + Superplasticizer = **Ton CO_2 = 315 .27**			
Calculation : 1000* Ton CO_2 / Volume = **Kg CO_2 / m^3 = 104.30**			

Saferock - Geopolymer concrete Volume = 3022.7 m^3 (A1-A3)			
	%	**Weight [ton]**	**Kg CO_2 per ton**
Total	100	7254.48	
Cement	14.34	1040.292	3.59
Aggregate	78.87	5721.608	7.52
Activator [KOH]	6.69	485.325	120.75
Superplasticizer	0.11	7.97992	536.5
Calculation : Weight [ton] * Kg CO_2 per ton = Cement + Aggregate + Activator + Superplasticizer = **Ton CO_2 = 109.65**			
Calculation : 1000* Ton CO_2 / Volume = **Kg CO_2 / m^3 = 36.27**			

4.2 Transport of concrete

According to Fabeko (Norsk Fabrikkbetongforening, 2023), the capacity of their concrete trucks is $6m^3$. The distance from the mixing plant to the customer is on average 25 kilometer round trip, with an average diesel consumption of 5.8 liters per 10 kilometer. Fabeko also estimated that 60 % of the delivered concrete must be pumped at the construction site, which results in an extra 3 liters of diesel per cubic meter of concrete. According to (Pedersen, Rune 2020) one liter diesel produce 2.66 kg CO_2. Table 4.2 shows the calculations for transportation.

The average distance travelled to and from the construction site is set to 25 kilometer. It's also assumed that 60% of the concrete needs to be pumped at the building site which results in 18 liters of extra diesel per truck load. Dividing the total kg CO_2 from transportation and pumping by the total concrete volume results in:

- kg CO_2 per m^3 = kg CO_2 / Total concrete volume = 11.22 kg CO_2 / m^3

When transportation and pumping at the construction site is included, the CO_2 emissions results in being 30.1% of the total CO_2 emissions for Saferock and 10.76% for Scwhenk's total CO_2 emissions. The calculations are shown below.

- **Percentage of CO_2 emissions from transportation compared to the concrete produced:**
- Percentage of Saferock's emissions = (11.22 / 36.27) * 100 = 30.1%
- Percentage of Scwhenk's low heat concrete =(11.22 / 104.3) * 100 = 10.76%

Table 4.2: Fuel estimation for concrete deliver to building site

Fuel Estimation		Unit
Total concrete volume	3022.7	m^3
Truck capacity	6	m^3
Truck loads needed : Total concrete volume / Truck Capacity	504	
40 % of the truck loads : 0.4 * Truck loads needed	202	
60 % of the truck loads : 0.4 * Truck loads needed	302	
Average distance traveled (Included return)	25	Kilometer
Average diesel consumption	5.8	Liter/10 kilometer
Diesel consumption for Pump (3liter per m^3 * Truck capacity)	18	Liter
Diesel usage without pump (The 40%): (Average distance traveled * Average diesel consumption * 40% of the truck loads)	2929	Liter
Diesel usage with pump (The 60%): (Average distance traveled * Average diesel consumption * 60% of the tuck loads) + (60% of the truck loads * Diesel consumption for pump)	9815	Liter
Total diesel usage : Diesel usage without pump + Diesel usage with pump	**12744**	**Liter**
kg CO_2 per liter diesel	2.66	Kg
Kg CO_2	33899.04	Kg
Ton CO_2	33.89904	Ton

4.3 Concrete including Reinforcement and delivery

This section compares the concrete types and includes transportation to the building site and reinforcement. The calculations below shows the reduction in kg CO_2 / m_3 when using Saferock's cement. Values used to calculate the reduction is shown in the table 4.3.

- Reduction = (155.85 - 87.83) = 68.02
- Percentage reduction = (Reduction / 155.85) * 100
- Percentage reduction = (68.02 / 155.85) * 100 = 43.65%

Using Saferock is the best alternative with a reduction of 43.65 % which is equivalent to a reduction of 205.62 Ton CO_2.

- Ton CO_2 reduced = 471.09 - 265.47 = 205.62 Ton CO_2

Table 4.3: Calculation of global warming potential in kg CO_2 equivalent per m^3 for concrete with reinforcement. The life cycle includes A1-A4.

Scwhenk - Lowheat concrete Volume = 3022.7 m^3 (A1-A3+A4)			
	%	**Weight [ton]**	**Kg CO_2 per ton**
Total	100	7254.48	
Cement	14.34	1040.292	257.58
Aggregate	78.87	5721.608	7.52
Water	6.69	485.325	0
Superplasticizer	0.11	7.97992	536.5
Reinforcement	100kg/m^3	302.27	393
Reinforcement Transportation to building site		302.27	10.2
Concrete Transportation to building site		7254.48	4.68
Calculation : Weight [ton] * Kg CO_2 per ton = Cement + Aggregate + Water + Superplasticizer + Reinforcement + Reinforcement Transportation to building site + Concrete transportation to building site= **Ton CO_2 = 471.09**			
Calculation : 1000* Ton CO_2 / Volume = **Kg CO_2 / m^3 = 155.85**			

Saferock - Geopolymer concrete Volume = 3022.7 m^3 (A1-A3+A4)			
	%	**Weight [ton]**	**Kg CO_2 per ton**
Total	100	7254.48	
Cement	14.34	1040.292	3.59
Aggregate	78.87	5721.608	7.52
Activator [KOH]	6.69	485.325	120.75
Superplasticizer	0.11	7.97992	536.5
Reinforcement	100kg/m^3	302.27	393
Reinforcement Transportation to building site		302.27	10.2
Concrete Transportation to building site		7254.48	4.68
Calculation : Weight [ton] * Kg CO_2 per ton = Cement + Aggregate + Activator + Superplasticizer + Reinforcement + Reinforcement transport to building site + Concrete transportation to building site = **Ton CO_2 = 265.47**			
Calculation : 1000* Ton CO_2 / Volume = **Kg CO_2 / m^3 = 87.83**			

4.4 Volume reduction with hollow cores

The hollow sections are 1.2m in width and have a thickness of 0.4m. If a hollow section were not used and the cross section was solid the cross sectional area would increase to an area of 1.2 * 0.4 = 0.48 m^2. The calculation below shows the volume reduction when utilizing hollow sections instead of a solid cross section.

- The c/s area of the hollow section = 0.2157 m^2
- Reduction = (0.48 - 0.2157) = 0.2643 m^2
- Percentage reduction (Reduction / 0.48) * 100
- Percentage reduction = (0.2643 / 0.48) = 55.06%

4.5 Discussion

The calculations show that Saferock's geopolymer concrete significantly lowers CO_2 emissions in comparison to Schwenk's low-heat concrete. It reduces emissions by 65.23% (excluding transport and reinforcement), and by 43.65% when these elements are factored in, making Saferock's geopolymer a preferable option for low emission constructions. Note also that the more parameters that are included in the calculations the less the % difference becomes. In this study the carbonation of the concrete throughout it's lifespan is not included, if this was included the differences between the two types of concrete would be reduced.
Saferock's geopolymer is still in its preliminary stages, and it's uncertain which type of activators will be chosen for the final product. The calculations were based on the assumption that a 35% NaOH solution would be used, resulting in 120.75 Kg of CO_2 per ton of activator. If the same concentration solution of KOH was used instead, it could further reduce emissions to 78.05 kg CO_2 per ton.
Another way to further cut emissions is to produce the NaOH locally as about 75% of emissions are due to transport. Since Saferock's Geopolymer is still in research and development phase, the final mass ratio is unknown. Hence, these calculations will need to be performed again once

the final mass ratio is determined.

Traditional cement types like Schwenk's will likely have lower associated emissions in the future. As mentioned in section 2.10, Norcem's new plant, Brevik, should be operational by the end of 2024. The plant aims to reduce emissions by 50% and it's likely that a similar reduction for Schwenk's low-heat cement emissions can be achieved in the near future.

However given the increased energy consumption that is needed for implementing carbon capture techniques, it may still be advantageous to opt for Saferock's geopolymer, even with equal emissions.

Currently, transport of concrete from the mixing plant to the construction site accounts for 30.1% of Saferock's emissions and 10.76% of Schwenk's emissions, based on Fabekko's data. This data assumes trucks are fuelled by fossil fuels. However, these trucks are likely to shift to biodiesel, hydrogen, or electric energy sources in the near future. This shift would reduce the emissions for both types of concrete.

Regardless of how eco-friendly the concrete is, it's crucial for engineers to design reliable buildings with smart solutions that can further cut down on material needs. As shown in the 'Volume reduction with hollow cores' calculation, using hollow cores instead of a solid floor separator can save 55.06% more concrete. Similar solutions for volume reduction applied a pressure on the engineers to find good solutions which requires less materials. This would in turn reduce emissions and cut costs for new constructions. Reducing the emissions is therefore required in every step, not only from the material supplier.

Chapter 5

Conclusion

Throughout this thesis, several methods for reducing the CO2 emission footprint from concrete production has been presented and applied on a given case. Both the mechanical and economical aspects have been considered.
The economical aspect is the recent introduction of carbon taxes and it's a significant contributor to encourage development of new sustainable alternatives. With carbon taxes reaching 100€ per ton CO_2 as seen in section 2.9 it forces the suppliers and producers to adopt CO_2 reducing methods and/or carbon capture technologies in order to survive in a competitive market. The CO_2 reduction methods presented with conclusion are:

- **Partial substitution of cement with SCM** to reduce the clinker content. An effective and fast approach to reduce emissions from concrete is to reduce the clinker content. It can be done by substituting parts of the cement with supplementary cementing materials such as fly ash, silica fumes and slag.
  This can be considered an effective waste management solution as it takes advantage of material that other industries see as waste. This may only be a temporary solution since SCM is currently categorized as waste with zero emissions however this may change in the future. With the implementation of increased carbon taxes, the value of SCM will likely increase. The price increase may lead to a slower transition to renewable energy sources, e.g. as the price of fly ash increases coal burning power plants might be profitable and therefore operational longer than they should.
  Natural pozzolanic materials might be a better solution for the future as it's found naturally from vulcanic ash. SCM's that are a byproduct from other harmful processes is currently classified as a zero emission product. The development and utilization of natural SCM's might go faster if this classification were changed.

- **Using alternative materials** such as geopolymer cement. The geopolymer cement from

Saferock showed a reduction of 43.65% CO_2 when compared Schenk's low heat concrete with the mass ratio assumed to be the same. This product has great potential in reducing the CO_2 footprint of the industry, given that the activator materials is sourced from local vendors as shown in section 4.3 and 4.5.

The final strength and mixing ratio are currently unknown since the product is still in development. If the final product has the same mechanical properties as regular Scwhenk's cement it's a good option for low emission projects.

- **Implementing CCS in cement production.** Carbon capture is a good solution to reduce the emissions. For each plant it's important to consider if the reduction in emissions are larger than the added emissions from the increased energy requirement from the capturing equipment combined with transport and storage of the CO_2.

  In Norway carbon capture is a great alternative as electrical prices are low, it is generated from renewable energy sources and the distance to storage is low (given storage location is in the north sea). In the future solutions like Carbfix could be a sustainable solution to offer carbon storage world wide, to avoid emissions from transportation.

- **Utilizing captured $\mathbf{CO_2}$**. In areas where captured CO_2 needs to be transported for long distances to be stored, a better solution might be to use the captured CO_2 as a resource to produce for example sustainable aviation fuels such as AIRMADE^{TM} which is in development at Air Company. If the concrete production is built close to an airport the emissions from transport is further reduced.

- **Possible scenario regarding emissions per $\mathbf{m^3}$ over the next 5 to 10 years**, From section 2.10, the new cement plant Breivik will use carbon capture techniques to reduce the emissions from production by 50%. Since Schwenk's cement is similar, it's likely that this cement type also will reduce their emissions similarly in the future. As shown in table 4.1 Schwenk's emissions are equal to 104.3 kg per m^3. With a 50% reduction this would lower the emissions to 52.15 kg per m^3. This reduction would lower the difference between Scwhenk's cement and Saferock's 36.27 kg per m^3.

  Even if Schwenk's cement was reduced to the same emissions as Saferock, carbon capture techniques increase the energy consumption. This could still make Saferock concrete a better option as it has a reduced energy requirement.

- **Sustainability** - Improved lifespan is a key aspect as well as low emissions. However, if the material is not durable over time and require more maintenance or have a reduced lifespan the reduction in emissions gained could potentially be lost. From table 2.3 Saferock states that their concrete are expected to have increased durability especially in acidic environment and at high temperature.
  Cement types like Scwhenks‘s low heat cement contains huge amount of SCM‘s and as shown in table 2.2 fly Ash, slag and silica fume improves permeability and corrosion resistance which are critical to increase the lifetime of the concrete. And with Scwhenks lower temperatures during hydration the risk of shrinkage cracks forming is reduced. This indicates that environmental concrete like Saferock and Scwhenk‘s should have an increased lifetime compared to regular Portland cement.

The biggest challenge lies in meeting the high energy demands with renewable energy. Since carbon capture requires significant energy this energy demand should ideally be powered by clean energy sources.
However, countries with limited renewable resources often rely on non-renewable sources to meet their electricity needs, which reduce the benefits gained from carbon capture. In such countries reducing the cement volume required, material substitution with SCM’s and using alternative materials can be good options.

Chapter 6

Further work

When new materials are introduced, it is important to consider the entire life cycle and not only focus on emissions during production. The following list shows further investigations possible as extensions to this thesis.

- Investigate the possibilities of recycling Saferock‘s concrete and compare it to how Schwenk's low heat concrete is recycled.
- When normal concrete is used, parts of the CO_2 emissions is absorbed by the concrete throughout its life span. If the carbonation absorbed was included in the emission calculations, Scwhenks's total emissions could be reduced.
- Investigate the the life cycle of the concrete, and include crushing of old concrete after end of life. Expose the concrete with CO_2 to force carbonatisation of all the materials since it's only the outside of the concrete that is carbonized through the life span. It might be possible to use this as landfiller or included in the aggregates as a form of carbon capture.
- When Saferock has developed a finished product, the calculations should be repeated with the final mass ratio and concentration of the activator. This also applies when transportation of the materials can be made more efficient by using electric or hydrogen vehicles.

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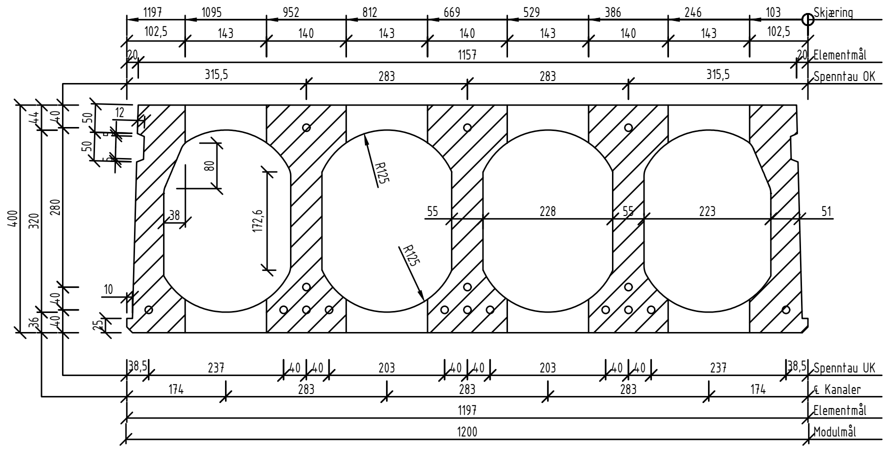
Vrålstad, Torbjørn (2022). Guest lecture by torbjørn vrålstad from saferock in byg605-betongteknologi in the autum of 2022. . (Accessed on 28/05/2023).

Webb,Comstedt,Karin (2023). Sweden first in the world with carbon-neutral cement plant. `https://www.cementa.se/en/sweden-first-in-the-world-with-carbon-neutral-cement-plant`. (Accessed on 12/3/2023).

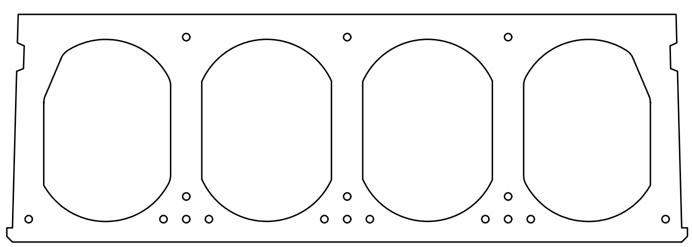
Appendix A

Data Sheets

ELEMENTTYPE HULLDEKKER HD400	Element: H40		
	Utgave 6	Dato 13.06.2022	Sign. HØR



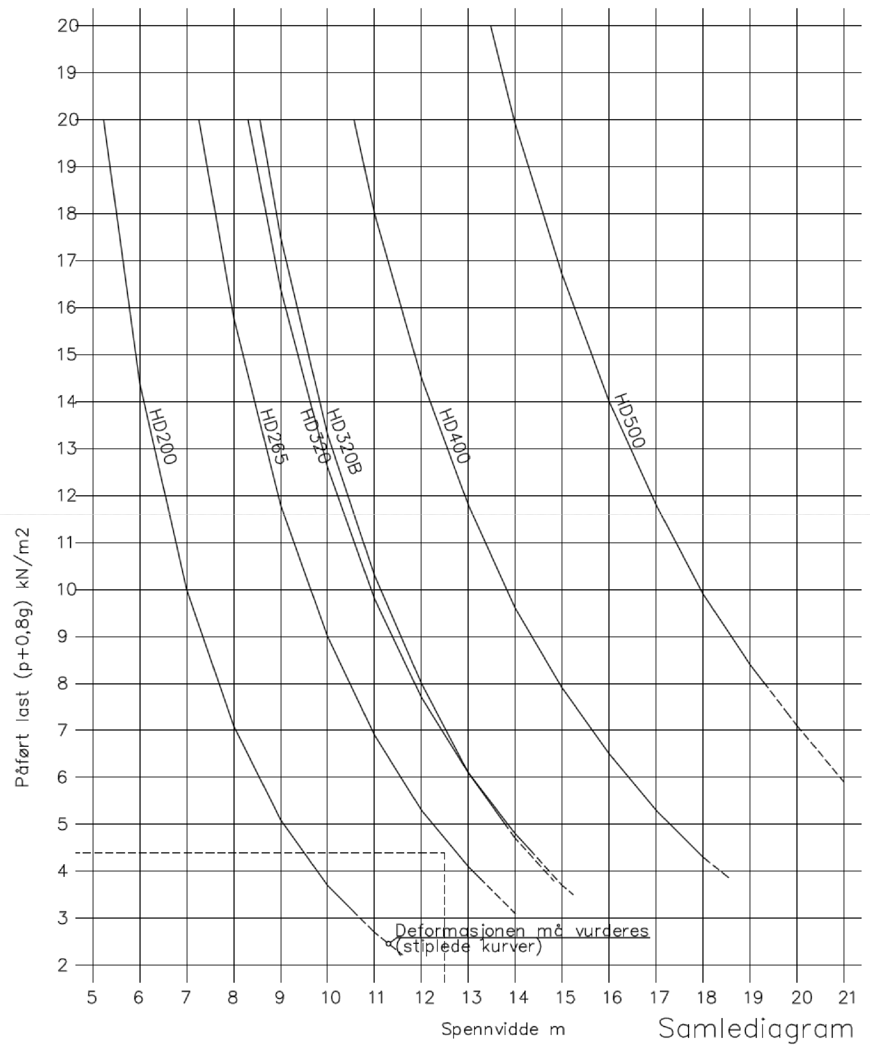
Egenvekt elementer: 458 kg/m^2 = 550 kg/m
Ferdig fuget dekke: 484 kg/m^2
Brutto areal A_c = 0,2157 m^2
Indre sleperør nr. L116135-C
Ytre sleperør nr. L117690-CA og L117690-CB
Elementene kan ikke langsskjæres i skraverte områder.



Spenncon

Figure A.1: This is the data sheet for the Spenncons Hollowcore HD400, this is included in the volume calculation to show the cross sectional area of the hollow section = 0.2157 m^3

Dimensjoneringsdiagram hulldekker



Last- og spennvidde -diagram for HD200-HD500. Kurvene angir maksimallast (bruksgrense) som kan påføres. Ved dimensjonering skal det kontrolleres at aktuell last angitt som p + 0,8g er mindre enn bæreevnen angitt i diagrammet.Ved forhåndsdimensjonering anbefales at man har omtrent 20 prosent reservekapasitet for utsparinger, uforutsette laster ol. Egenvekten av HD skal ikke medtas i påført last.

Eksempel på bruk av diagram: Dekke med spennvidde 12,5 meter, påstøp g = 0,5 kN/m2 og nyttelast lik p = 4,0 kN/m2 gir påført last 0,8 x 0,5 + 4,0 = 4,4 kN/m2. Nødvendig dimensjon: HD265.

Teknisk dokumentasjon 24.11.2011

Spenncon

Figure A.2: Spenncon Hollowcore table used to calulate the required hollow core section for the floor and roof. The equation to calculate applied load is shown and explained in the bottom of the figure (Spenncon AS, 2011).

SCHWENK

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Miljøpåvirkning (Environmental impact)

Parameter		Unit	A1	A2	A3	A4
	GWP-total	kg CO_2 -eq	1,05E+00	8,33E+00	2,13E+02	2,97E+01
	GWP-fossil	kg CO_2 -eq	1,03E+00	8,33E+00	2,12E+02	2,97E+01
	GWP-biogenic	kg CO_2 -eq	1,23E-02	3,61E-03	8,31E-01	1,42E-02
	GWP-luluc	kg CO_2 -eq	8,73E-04	2,65E-03	5,98E-02	1,43E-02
	ODP	kg CFC11 -eq	1,51E-07	2,00E-06	2,04E-06	5,45E-06
	AP	mol H+ -eq	9,97E-03	2,80E-02	3,00E-01	5,22E-01
	EP-FreshWater	kg P -eq	3,47E-05	6,72E-05	7,54E-03	3,05E-04
	EP-Marine	kg N -eq	2,98E-03	6,49E-03	6,33E-02	1,58E-01
	EP-Terrestial	mol N eq	3,91E-02	7,22E-02	9,00E-01	1,76E+00
	POCP	kg NMVOC -eq	9,14E-03	2,73E-02	1,75E-01	4,65E-01
	ADP-minerals&metals[1]	Kg Sb-eq	3,72E-05	1,47E-04	4,11E-04	1,69E-04
	ADP-fossil[1]	MJ	1,51E+01	1,35E+02	7,16E+02	3,87E+02
	WDP[1]	m^3	3,18E+02	1,04E+02	6,77E+03	2,31E+02

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

"Leseeksempel: 9,0 E-03 = 9,0*10 -3 = 0,009"
*INA Indicator Not Assessed

1. The results of this environmental impact indicator shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator
3. Eutrophication aquatic freshwater shall be in kg P-eq., there is a typo in EN 15804:2012+A2:2019 regarding this unit. Eutrophication calculated as PO4-eq is presented on page 11

Remarks to environmental impacts

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Figure A.3: Total global warming potential for Schwenk Lowheat cement is shown at the top as GWP. This is one of twelve pages of the EPD, publised by EPD norge SCHWENK Norge AS (2023).

LCA: Resultater

Resultater for miljøpåvirkningskategorier i de ulike modulene er presentert nedenfor.
Deklarert enhet er per 1 tonn Betongtilslag, 0/8 mm, 4/8 mm, 8/16 mm, 16/22 mm

Systemgrenser (X = inkludert, MID = modul er ikke deklarert, MIR = modul ikke relevant

Produktfasen			Konstruksjon		Bruksfase							Sluttfase				Etter endt levetid
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjon og installasjon	Bruk	Vedlikehold	Reparasjon	Utskiftninger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallshåndtering	Avfall til sluttbehandling	Gjenbruk-gjenvinning-resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID

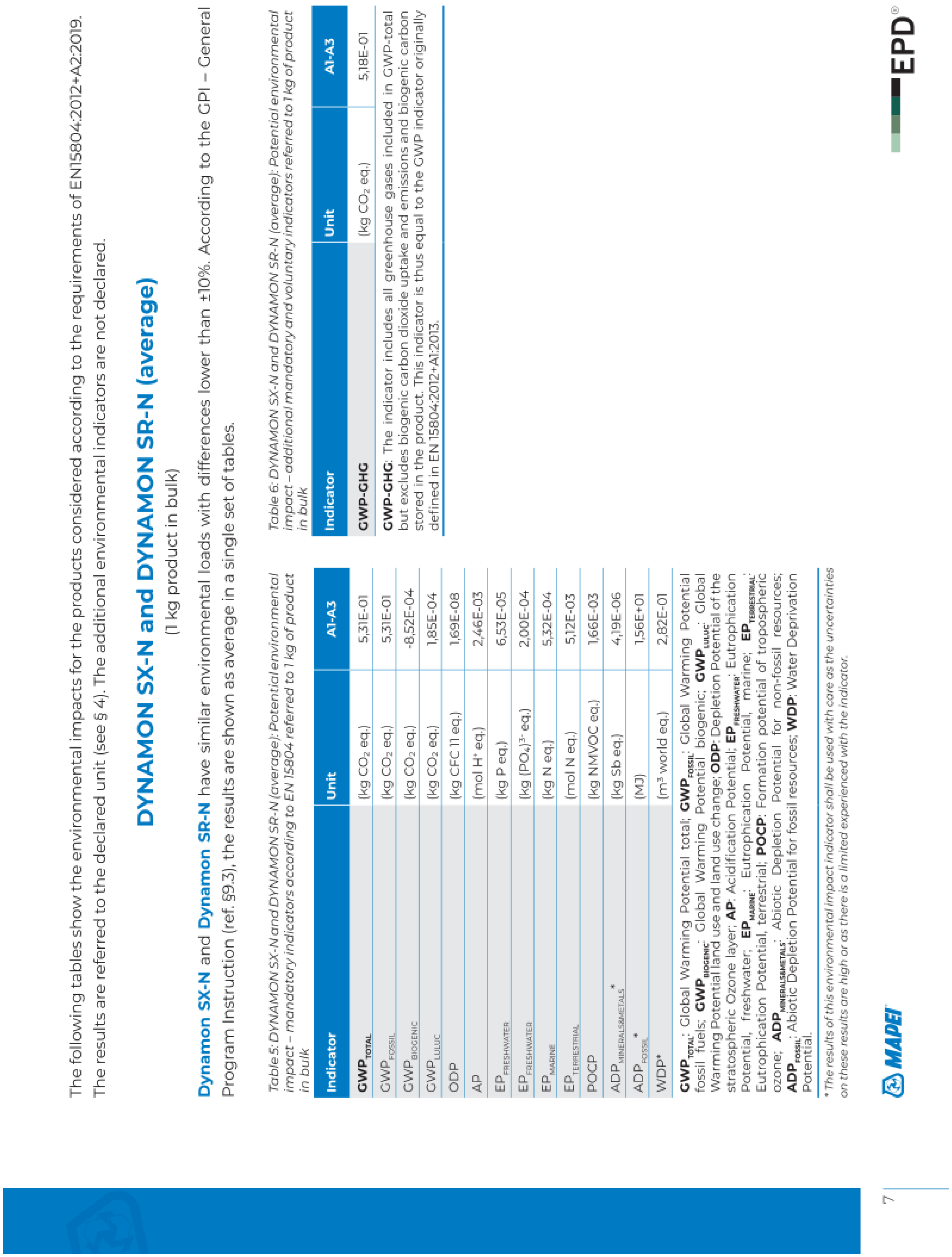
Miljøpåvirkning

Parameter	Enhet	A1-A3	A4
GWP	kg CO2 - ekv.	1,88E+00	1,41E+00
ODP	kg CFC11- ekv.	3,01E-07	2,26E-07
POCP	kg C2H4 - ekv.	3,71E-04	9,61E-04
AP	kg SO2 - ekv.	1,23E-02	2,98E-02
EP	kg PO43-- ekv	3,08E-03	3,13E-03
ADPM	kg Sb - ekv	3,07E-06	3,17E-07
ADPE	MJ	2,67E+01	2,04E+01

GWP Globalt oppvarmingspotensial; ODP Potensial for nedbryting av stratosfærisk ozon; POCP Potensial for fotokjemisk oksidantdanning; AP Forsurningspotensial for kilder på land og vann; EP Overgjødslingspotensial; ADPM Abiotisk uttømmingspotensial for ikke-fossile ressurser; ADPE Abiotisk uttømmingspotensial for fossile ressurser

NEPD-3125-1784-NO Betongtilslag, 0/8 mm, 4/8 mm, 8/16 mm, 16/22 mm (ver2-281021) 6/9

Figure A.4: Total global warming potential for Forsand sand company aggregates is shown in the top of the table as GWP. This is one of nine pages of the EPD publised by EPD norge Haukalid , Rune (2021).



The following tables show the environmental impacts for the products considered according to the requirements of EN15804:2012+A2:2019. The results are referred to the declared unit (see § 4). The additional environmental indicators are not declared.

DYNAMON SX-N and DYNAMON SR-N (average)

(1 kg product in bulk)

Dynamon SX-N and **Dynamon SR-N** have similar environmental loads with differences lower than ±10%. According to the GPI – General Program Instruction (ref. §9.3), the results are shown as average in a single set of tables.

Table 5: DYNAMON SX-N and DYNAMON SR-N (average): Potential environmental impact – mandatory indicators according to EN 15804 referred to 1 kg of product in bulk

Indicator	Unit	A1-A3
GWP_{TOTAL}	(kg CO_2 eq.)	5,31E-01
GWP_{FOSSIL}	(kg CO_2 eq.)	5,31E-01
$GWP_{BIOGENIC}$	(kg CO_2 eq.)	-8,52E-04
GWP_{LULUC}	(kg CO_2 eq.)	1,85E-04
ODP	(kg CFC 11 eq.)	1,69E-08
AP	(mol H^+ eq.)	2,46E-03
$EP_{FRESHWATER}$	(kg P eq.)	6,53E-05
$EP_{FRESHWATER}$	(kg $(PO_4)^{3-}$ eq.)	2,00E-04
EP_{MARINE}	(kg N eq.)	5,32E-04
$EP_{TERRESTRIAL}$	(mol N eq.)	5,12E-03
POCP	(kg NMVOC eq.)	1,66E-03
$ADP_{MINERALS\&METALS}$*	(kg Sb eq.)	4,19E-06
ADP_{FOSSIL}*	(MJ)	1,56E+01
WDP*	(m^3 world eq.)	2,82E-01

GWP_{TOTAL}: Global Warming Potential total; **GWP_{FOSSIL}**: Global Warming Potential fossil fuels; **$GWP_{BIOGENIC}$**: Global Warming Potential biogenic; **GWP_{LULUC}**: Global Warming Potential land use and land use change; **ODP**: Depletion Potential of the stratospheric Ozone layer; **AP**: Acidification Potential; **$EP_{FRESHWATER}$**: Eutrophication Potential, freshwater; **EP_{MARINE}**: Eutrophication Potential, marine; **$EP_{TERRESTRIAL}$**: Eutrophication Potential, terrestrial; **POCP**: Formation potential of tropospheric ozone; **$ADP_{MINERALS\&METALS}$**: Abiotic Depletion Potential for non-fossil resources; **ADP_{FOSSIL}**: Abiotic Depletion Potential for fossil resources; **WDP**: Water Deprivation Potential.

** The results of this environmental impact indicator shall be used with care as the uncertainties on these results are high or as there is a limited experienced with the indicator.*

Table 6: DYNAMON SX-N and DYNAMON SR-N (average): Potential environmental impact – additional mandatory and voluntary indicators referred to 1 kg of product in bulk

Indicator	Unit	A1-A3
GWP-GHG	(kg CO_2 eq.)	5,18E-01

GWP-GHG: The indicator includes all greenhouse gases included in GWP-total but excludes biogenic carbon dioxide uptake and emissions and biogenic carbon stored in the product. This indicator is thus equal to the GWP indicator originally defined in EN 15804:2012+A1:2013.

MAPEI

EPD®

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Figure A.5: Total global warming potential for Mapei SX-N superplastiziser, value is shown on the left side as GWP. This is one page of the EPD published by EPD Norge Mapei Norge AS, (2021).

Borregaard

Environmental impact				
Parameter	Unit	A1-A3	A4	A1-A4
GWP	kg CO_2-eqv	7,00E+01	2,75E+02	3,45E+02
ODP	kg CFC11-eqv	8,40E-06	5,06E-05	5,90E-05
POCP	kg C_2H_4-eqv	1,88E-02	2,71E-02	4,58E-02
AP	kg SO_2-eqv	4,50E-01	7,34E-01	1,18E+00
EP	kg PO_4^{3-}-eqv	1,39E-01	1,26E-01	2,65E-01
ADPM	kg Sb-eqv	1,53E-03	1,63E-05	1,54E-03
ADPE	MJ	7,01E+02	3,91E+03	4,61E+03

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

Resource use				
Parameter	Unit	A1-A3	A4	A1-A4
RPEE	MJ	3,03E+03	5,48E+00	3,04E+03
RPEM	MJ	0,00E+00	0,00E+00	0,00E+00
TPE	MJ	3,04E+03	5,48E+00	3,04E+03
NRPE	MJ	1,07E+03	3,91E+03	4,99E+03
NRPM	MJ	0,00E+00	0,00E+00	0,00E+00
TRPE	MJ	1,07E+03	3,91E+03	4,99E+03
SM	kg	0,00E+00	0,00E+00	0,00E+00
RSF	MJ	0,00E+00	0,00E+00	0,00E+00
NRSF	MJ	0,00E+00	0,00E+00	0,00E+00
W	m^3	2,09E+01	5,86E-03	2,09E+01

RPEE Renewable primary energy resources used as energy carrier; RPEM Renewable primary energy resources used as raw materials; TPE Total use of renewable primary energy resources; NRPE Non renewable primary energy resources used as energy carrier; NRPM Non renewable primary energy resources used as materials; TRPE Total use of non renewable primary energy resources; SM Use of secondary materials; RSF Use of renewable secondary fuels; NRSF Use of non renewable secondary fuels; W Use of net fresh water

End of life - Waste				
Parameter	Unit	A1-A3	A4	A1-A4
HW	kg	1,61E-03	1,04E-02	1,20E-02
NHW	kg	1,29E+02	1,47E+00	1,31E+02
RW	kg	6,64E-03	2,84E-02	3,50E-02

HW Hazardous waste disposed; NHW Non hazardous waste disposed; RW Radioactive waste disposed

End of life - Output flow				
Parameter	Unit	A1-A3	A4	A1-A4
CR	kg	0,00E+00	0,00E+00	0,00E+00
MR	kg	3,69E-02	0,00E+00	3,69E-02
MER	kg	6,61E+00	0,00E+00	6,61E+00
EEE	MJ	0,00E+00	0,00E+00	0,00E+00
ETE	MJ	0,00E+00	0,00E+00	0,00E+00

CR Components for reuse; MR Materials for recycling; MER Materials for energy recovery; EEE Exported electric energy; ETE Exported thermal energy

Reading example: 9.0 E-03 = $9.0*10^{-3}$ = 0.009

NEPD-3016-1686-EN Sodium hydroxide (ver2-250821)

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Figure A.6: Total global warming potential for the NaOH used as activator for Saferock's concrete. Value is shown as GWP at the top of the table. This is one of the pages in the EPD published by EPD norge Borregaard AS, (2021).

NORSK STÅL

LCA: Resultater

LCA resultatene er presentert under for den deklarerte enheten som er definert på side 2 av EPD dokumentet.

Systemgrenser (X=inkludert, MND=modul ikke deklarert, MNR=modul ikke relevant)

Product stage			Construction installation stage		User stage							End of life stage				.	Beyond the system bondaries
Råmaterialer	Transport	Tilvirkning	Transport	Konstruksjons/ installasjonsfase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til sluttbehandling		Gjenbruk/gjenvinning/ resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	.	D
X	X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	X	X	X	X	.	X

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1-A3	A4	C1	C2	C3	C4	D
GWP	kg CO_2 -eq	3,93E-01	1,02E-02	5,67E-02	1,02E-02	9,90E-05	1,04E-04	5,47E-01
ODP	kg CFC11 -eq	1,34E-08	1,92E-09	9,82E-09	1,92E-09	1,10E-11	3,40E-11	2,25E-08
POCP	kg C_2H_4-eq	7,97E-05	1,54E-06	9,50E-06	1,54E-06	2,71E-08	3,16E-08	3,82E-04
AP	kg SO_2 -eq	1,29E-03	2,40E-05	4,30E-04	2,40E-05	6,17E-07	7,56E-07	2,44E-03
EP	kg PO_4^{3-} -eq	2,22E-04	3,15E-06	9,36E-05	3,15E-06	9,49E-08	1,33E-07	8,13E-04
ADPM	kg Sb -eq	3,19E-07	3,17E-08	2,45E-10	3,17E-08	7,00E-12	2,00E-12	1,06E-05
ADPE	MJ	3,47E+00	1,54E-01	7,84E-01	1,54E-01	9,21E-04	2,91E-03	5,14E+00

GWP Global warming potential; ODP Depletion potential of the stratospheric ozone layer; POCP Formation potential of tropospheric photochemical oxidants; AP Acidification potential of land and water; EP Eutrophication potential; ADPM Abiotic depletion potential for non fossil resources; ADPE Abiotic depletion potential for fossil resources

Leseeksempel 9,0 E-03 = 9,0*10 -3 = 0,009
*INA Indicator Not Assessed

Merknad om miljøpåvirkningen

Denne generelle EPDen dekker varer fra flere produsenter, resirkuleringsgraden på innsatsmaterialet er opptil 98,5%.
Ved behov kan Norsk Stål AS utarbeide prosjekt-/leveransespesifikk EPD på forespørsel.

NEPD-2676-1376-NO Kamstål til bruk i betong

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Figure A.7: Total global warming potential for the reinforcement used in both concretes. Value is shown as GWP at the top of the table. This is one of the eight pages from the EPD published by EPD norge Norsk Stål AS, (2021).