CHALMERS
UNIVERSITY OF TECHNOLOGY

Concrete change

Analyzing strategies to reduce the climate impact of cement

Master's thesis in Industrial Engineering

Pontus Arvidsson

Department of Energy Technology

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2020
www.chalmers.se

Concrete change: Analyzing strategies to reduce the climate impact of cement

PONTUS ARVIDSSON

Department of Energy Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

[Chalmers Reproservice]
Göteborg, Sweden 2020

Concrete Change: Analyzing strategies to reduce climate impact of cement

PONTUS ARVIDSSON

Department of Energy Technology

Chalmers University of Technology

Abstract

To be able to reach the Paris agreement significant efforts to reduce greenhouse gas emission will be required in all areas of society. The emissions from the construction sector is a large contributor to the global emissions. Within the construction sector a large contribution to emission comes from the concrete production. It is an important area to reduce the emissions in since it is essential in many areas of society for e.g. buildings and infrastructure.

The largest contributor to emissions in the concrete industry is the production of cement, which accounts for 8% of global CO_2-emissions. Nearly 60% of these emissions comes from the calcination reaction during the production of cement clinker. Therefore, the cement industry faces a different challenge than other industries, since shifting towards alternative fuels will not be enough. Carbon capture and storage will most likely be necessary for this industry, but since this is far from available in a commercial scale in the near future other measures must be taken before that is implemented.

The main goal of this thesis is to construct an overview of the cement material flow in the Swedish society and mapping the end uses of cement. Due to a lack of actual industrial data, an approximation model based on standard cement products was created. In extension to this model, a set of 5 scenarios was created where various methods to reduce the CO_2 emissions from cement were illustrated. The results from the scenarios was also compared to representative data from other EU countries. The comparison showed that Sweden have a long way to go in this area of CO_2 emission reduction regarding both cement clinker levels and cement and binder intensity in concrete.

This thesis shows the importance of having a thorough statistical base describing different end-uses of cement containing products to be able to see the emission reduction potential on all levels of the usage of the materials. There is a need for accurate data from the mortar, screed and render businesses to allow for a more detailed material flow, as well as more advanced statistics from the concrete industry, related to both end-uses, binder intensity and cement types used in various applications. This type of data would be very useful to be able to analyze the usage (and potential over-usage) of cement and cement clinker in constructions and how to reduce both the cement use, the cement clinker use and the associated CO_2 emissions.

Keywords: Cement, Concrete, Emission reduction, Statistics, Material flow

Sammanfattning

För att kunna uppnå Parisavtalets mål så måste det göras betydande insatser för att reducera utsläppen av växthusgaser inom alla samhällsområden. Utsläppen från bygg- och anläggningssektorn står för en betydande del av de globala utsläppen av växthusgaser. Inom bygg- och anläggningssektorn kommer en stor del av utsläppen från produktionen av betong. Eftersom betong är ett viktigt konstruktionsmaterial inom till exempel infrastruktur och bostäder är det viktigt att hitta åtgärder för att minska utsläppen från cement och betongproduktion.

Huvuddelen av utsläppen från betongproduktion härrör från produktionen av cement som står för ungefär 8% av de globala utsläppen av CO_2. Nästan 60% av dessa utsläpp kommer från kalcineringsreaktionen som sker under tillverkningen av cementklinker. Cementindustrin möter därför en annorlunda utmaning jämfört med många andra industrier då det inte kommer att räcka att enbart byta till fossilfria bränslen. Infångning och lagring av CO_2 kommer troligtvis att vara nödvändigt. Dock är denna teknik inte redo att börja användas på en kommersiell skala inom den närmsta framtiden vilket medför att andra åtgärder behöver göras innan denna teknik är redo att implementeras.

Det huvudsakliga målet med denna uppsats är att översiktligt illustrera materialflödet av cement och betong inom det svenska samhället och kartlägga dess användningsområden. På grund av brist av aktuella data från industrin så fick en approximationsmodell skapas för att illustrera detta, vilken baserades på värden på standardprodukter av cement samt volymdata från den inhemska betongindustrin. Utöver detta så skapades 5 olika scenarier där olika metoder tillämpas för att minska utsläppen av CO_2. Dessa resultat jämfördes även mot andra EU-länder vilket visade att Sverige har en lång väg kvar för att minska utsläppen både utifrån en reduktion av halten cementklinker samt mängden cement som används i betong.

Detta arbete visar att det är viktigt med utförlig statistik som beskriver hur cement och betong används för att kunna analysera vilken potential olika metoder har för att minska utsläppen genom hela leverantörskedjan. Det finns ett behov av bättre data avseende puts och murbruk för att möjliggöra ett mer detaljerat materialflöde, likaväl som mer avancerad statistik från betongindustrin, relaterad till både slutanvändning, bindemedelsintensitet och cementtyper som används i olika applikationer. Denna typ av data skulle vara mycket användbar för att kunna analysera användningen (och potentiell överanvändning) av cement och cementklinker i byggandet och hur man kan minska både cementanvändningen, cementklinkeranvändningen och de tillhörande koldioxidutsläppen.

Content

Summary of Figures

Summary of Tables

1. Introduction

Today the average temperature on the earth is increasing to levels that affect ecosystems and societies around the world. The effects that follows includes for example raising sea levels, desertification and mass extinction of animal species. The large increase in greenhouse gas (GHG) emissions, which has led to the current temperature increase of around 1° Celsius, began when the human society started to industrialize [1]. With industrialization, mass production became possible and the performance of various aspects of society could increase much quicker than before. New types of machinery were invented to help society, such as trains fueled by coal combustion. While all of this raised the quality of life to a level that before was unimaginable, the problems that followed were massive increases in GHGs in the atmosphere, intensifying the greenhouse effect. At the time however, there was no awareness or understanding of this problem. The problem started to become more apparent in the later parts of the 20th century.

Reducing the emissions is no easy task, but the first world-wide climate protocol was adopted in Kyoto 1997, which was ratified and signed by most of the UN members (with some significant exemptions including the US). A large new agreement was made in Paris in 2015, where it was decided to keep the average temperature to well below 2° Celsius compared to pre-industrial levels. It also includes that if possible, efforts towards limiting the temperature increase to 1.5° Celsius should be carried out. The agreement allows countries to set their own targets, while introducing instruments to ratchet up national ambition trough provisions on transparency and regular reporting [2].

The EU have their own separate climate goals with a long-term goal of net-zero emissions by 2050 (for all countries but Poland), with intermediate targets of 20% reduction of GHG emissions compared to 1990 levels [3] for 2020 and 40% reduction compared to 1990 for 2030 (with enhanced ambition to 2030 under negotiation) [4]. The goal to have a climate neutral economy by 2050 comes with great challenges, but while the rise of emission previously followed the economic growth patterns, there has been a successful decoupling of the economy from the emissions. Compared to 1990 levels the emissions have been cut by 22% while the GDP has risen by 58% within the EU [5].

Sweden has set more ambitious climate targets than the EU, with a 40% reduction of GHGs in 2020 compared to the levels of 1990, a reduction of 63% to 2030 and the long-term goal is to have net-zero emissions in 2045 (defined as at least 85% domestic reductions with the remaining achieved through so-called supplementary measures, e.g. reduction overseas or capture and storage of carbon dioxide) [6].

The cement industry is a significant source of emissions and account for roughly 8% of the worlds CO_2 emissions today [7], which means all improvements that can be made within this single industry benefits the emission reduction goals. The industry has difficult challenges regarding emissions reduction which are described in detail in this report. Cement is not used on its own but is a component in e.g. concrete and in mortar, screed and render. As cement has many end use applications, solutions are complex, since it is difficult to find measures that apply to a wide variety of areas. Previous studies suggest that there is a significant potential to reduce the climate impact of new concrete structures if applying a combination of measures upstream (in the primary production of cement) and downstream (e.g. reducing the amount of cement and concrete used for a specific function) in the concrete supply chain. However, to provide a realistic estimate of the potential for downstream mitigation measures, there is a need for a better description of how cement and concrete is used today [6][7][10]. The possibilities to reduce cement use are highly dependent on the application. Therefore, data on cement use in different applications are needed. Data on the origin of cement in concrete is also required for a consistent low carbon transition strategy for the construction industry. Today, particularly in Sweden, there is a lack of a detailed knowledge about the material flows related to cement and concrete use [11]. If that existed, it would be easier to perform more accurate assessments of the potential for different measures to reduce emissions and increase resource efficiency in the production and use of cement and concrete.

1.1 Aim and scope

To provide a realistic estimate of the potential to reduce the climate impact of new concrete structures it is important to have a relatively detailed understanding of how cement and concrete is used in society. The objective of the thesis is to assess and estimate the material flows and end uses of cement in Sweden. The goal is to construct a map that shows a visual representation of the material flow through the construction supply chains, what type of cement is used and where. This study has chosen to focus on creating and estimating the cement flow rather than developing a detailed map of the end use of concrete, mortar, screed and render due to the overall lack of data and the multiple actors of these industries compared to the cement market. This choice of focus makes it is easier to estimate the use of cement and maintaining a higher accuracy of relevant data. This study also features emissions comparisons and will use the developed map to explore different scenarios examining the effects of changes in cement types, clinker intensity and binder intensity in concrete.

1.2 Problem description and background of the cement industry

Concrete has been used through society since ancient civilizations like Egypt, Greece and the Roman empire. Early binders for concrete were volcanic ashes, which today is known as natural pozzolanic cement. The discovery of concrete allowed these civilizations to emerge and especially the Roman empire could establish themselves as a dominant empire in Europe. Concrete enabled them to build better roads and build aqueducts to transport fresh water to their cities. When the Roman empire fell in the 5th century a lot of knowledge about concrete was lost. In the centuries to follow a lot of masonry processes were done through carbonation of lime which was a very slow process compared to pozzolanic cement. It was not until early in the 19th century that the currently most common type of cement was invented in 1824 when Joseph Aspdin took a patent on Portland cement. Portland cement is made of cement clinker, grounded limestone and possible other filler materials or binders [12]. Later in the 19th century the first version of the modern Portland cement was created by Isaac Johnson in 1845.

The use of concrete expanded rapidly after World War 2, at first rebuilding and then contributing to further development of the Western parts of the world. Even if countries like China is by far the highest consumer of concrete today, their use of concrete increased later. As can be seen in Figure 1, global cement production driven by Chinese development took off closer towards the 1990-2000 when China started to make major investments in infrastructure to modernize the country.

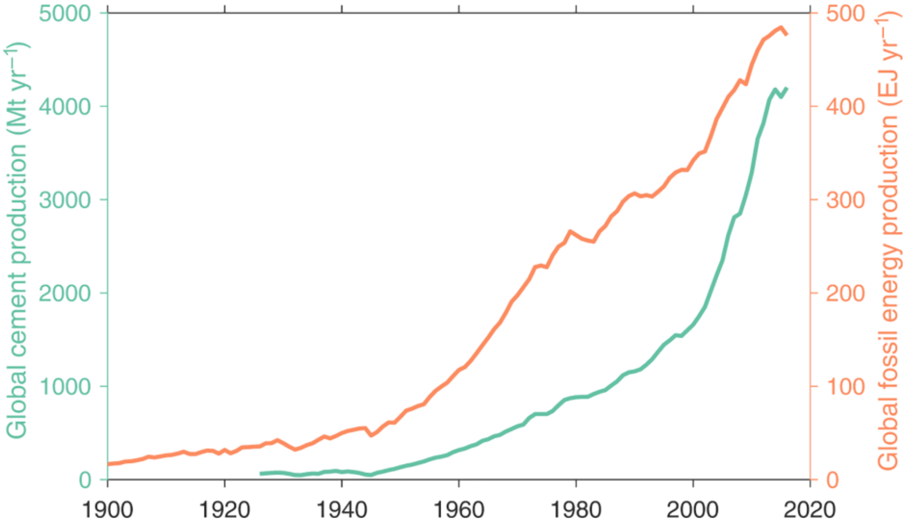


Figure 1 A graph showing the production of cement and the energy production from fossil fuels [13].

The production has taken a small halt in later years as China's production increase has stalled. However, the production has still increased 4-fold since 1990 [13].

Today, concrete is the world's most used product, and the use of concrete is expected to increase in many parts of the world [14]. Conventional concrete is made of aggregates, water and cement produced from limestone, which are all materials available in most parts of the world. Concrete is used everywhere in society, being one of the most important building materials in the construction industry. The reason concrete is valuable as a construction material is that it is available in abundance, has great flexibility and is very cheap. It can be precast in factories while also offering the possibility to be produced and molded right at the building site. It is also a very strong material which is a valuable attribute, particularly in parts of the world where natural disasters occur at a more frequent rate [7]. Cement is a crucial part in concrete since it is the binding agent. Non-concrete applications of cements also exist and have three different major areas. Mortars are used to bind bricks together, screed is used to coat floors and renders are used as finishing touches on wall surfaces [15].

Most of the emissions in the concrete production chain is the formation of the clinker in cement. In many other industrial sectors, it is possible to reduce GHG emissions via fuel substitution towards biofuels or electrification, while in cement roughly 50-60% of the emissions come from the chemical reaction itself, the reaction where limestone is calcinated to become Portland cement clinker [7].

A common way to reduce GHG emissions in concrete is to replace a share of the Portland cement clinker in cement with fly-ash and/or ground granulated blast furnace slag (GGBFS), the use of grounded limestone has also seen an increase in usage in recent years. These are known as supplementary cementitious materials (SCM). Fly-ash is a byproduct from coal-fired power plants and GGBFS is a residue product from the blast furnaces used to produce steel from iron ore [16]. There are several up- and downsides with these replacements. While reducing the emissions, their use may also imply some alteration to the concrete properties. There are also supply issues, due to coal power plants being shut down as electricity production is going in a green direction with renewable electricity generation outcompeting coal in line with wind and solar power generation costs coming down [17]. While GGBFS is likely to be around for longer, blast furnace is likely to be replaced by low-emission steel production processes in the long term (e.g. hydrogen reduction with hydrogen produced by electrolysis). Further, there is only a single blast furnace in Sweden that has this type of slag. Swedish producers thus have to import GGBFS from other steel-producing countries like Germany and France, implying tight competition [17]. Other possible SCMs are pozzolanic materials, clays or more limestone. In terms of replacing Portland cement clinker, one of the major problems is thus the large quantities being used, which makes the list of possible replacements very thin [7].

Another measure that can be taken alongside the use of SCMs mixed with the Portland cement clinker is to use carbon capture and storage (CCS). The basic idea is to capture the carbon dioxide before it is emitted and then store it underground. This technology is however very capital intensive and require investments in both capture and transport infrastructure, along with underground storage for the carbon dioxide. There is thus a need for further research and development for deployment of CCS to reach large scales as well as sufficient policy instruments and market demand for low-carbon cement to achieve economic feasibility for CCS [7]. However, the potential for CCS is greater compared to other industries since the cement industry do not have many different productions sites but rather large factories. For example, Sweden has two production sites located in Slite and Skövde. While research demonstrates room for improvements through material efficiency, recipe optimization and fuel efficiency, CCS will be required to lower the emissions below certain thresholds or to reach the long-term goal of zero emissions [18]. Alongside CCS there are also projects focusing on CCU, carbon capture and utilization. The aim of this technology is to recycle and use CO_2 within other industries like the chemical industry sector. However, these technologies are still not fully developed on a commercial scale and currently only exists in smaller experimental projects [19].

Another difference regarding the cement industry compared to other sectors is that there are few producers in the market. In Sweden Cementa is the only company to produce cement [18]. Companies with a limited competition on a certain business market are less inclined to change their business model unless laws regarding emissions are changed, which means that stricter governmental regulations would need to be applied to drive companies to invest in actions to reduce the climate impact [9]. With a large share of the market for a material that is a necessity in the society, the large investments required to achieve emission reductions is associated with significant risks, as it increases production costs and could result in customers choosing to import cement from international producers rather than paying higher prices, so called carbon leakage [9]. The cement industry is a part of the EU ETS system which is the emission trading system within the EU. However, the price of the emission rights and the current technology costs, means that at least to date it is cheaper to buy more emission rights rather than to invest in technology [18]. Limited market demand for alternative cement products also reinforces existing business models. A strong market demand would thus be an alternative, but both producers and customers are very cautious with change as it would mean the production planning and methods might need to be altered, which comes with extra costs, as well as due to the need to guarantee durability, since it would of course be disastrous if a building collapsed due to poor testing of new cements or concrete recipes [7].

Due to the large volumes of cement being produced large quantities of limestone has been necessary for the process, which means that large quarries have been created. There are thus also challenges related to the mining of limestone to produce traditional cement. Since there is a large need for limestone it also means that the local environment effects may be significant. One of the Swedish cement factories is located in Slite, on Gotland, where Cementa recently applied to extend their mining rights of limestone. This got denied for different reasons, among them being that the area contains many red listed species and biotopes of high value. There were also other justifications such as not including any objective analysis of how the demand for limestone cement will develop in the future [20]. While the expansion was finally approved in early 2020, it was only extended for twenty years and contained clauses for fines related to ecosystem damage [21]. To keep up with the rapid increase of cement manufacturing (as per Figure 1), the size of quarries keeps growing in some cases and causes new quarries to open in other places. Therefore, it is a strong interest to reduce the material intensity in the final concrete structures. Further, there is often 20-30% more cement in the concrete mix today than what is required by standards, which occurs for two reasons: over-specification of cement by concrete producers, and higher exposure classes for the concrete than the situation demands [22]. In Sweden, we are also facing an additional challenge in that faster construction processes have led to highly set drying requirements, for example for slabs covered with plastic or parquet flooring. To meet these requirements, concrete with very high cement content are used. There is thus a large potential for the cement demand to be reduced by changing construction production planning to suit new cement types, adjust concrete recipes depending on the specified flooring and add a screed layers or apply floating flooring solutions to create a buffer zone between concrete and flooring [23]. Although a majority of the cement is used in concrete there is still a large usage of non-concrete cement products as can be seen in Figure 7, but due to lack of data and more actors involved there is a heavier focus on the cement used in concrete.

While there is a strong interest in reducing the climate impact caused by cement production, demonstrated for example by the Swedish cement, concrete and construction industries' 'Roadmaps for fossil-free competitiveness', little is known about the end-uses of cement and concrete in Sweden [11][24]. As can be seen in Figure 2, the industries are entwined, which increases the complexity of reducing emissions via downstream abatement measures. While only one cement manufacturer exists in Sweden, cement is also imported and on the concrete side there are many different producers, which makes obtaining data difficult.

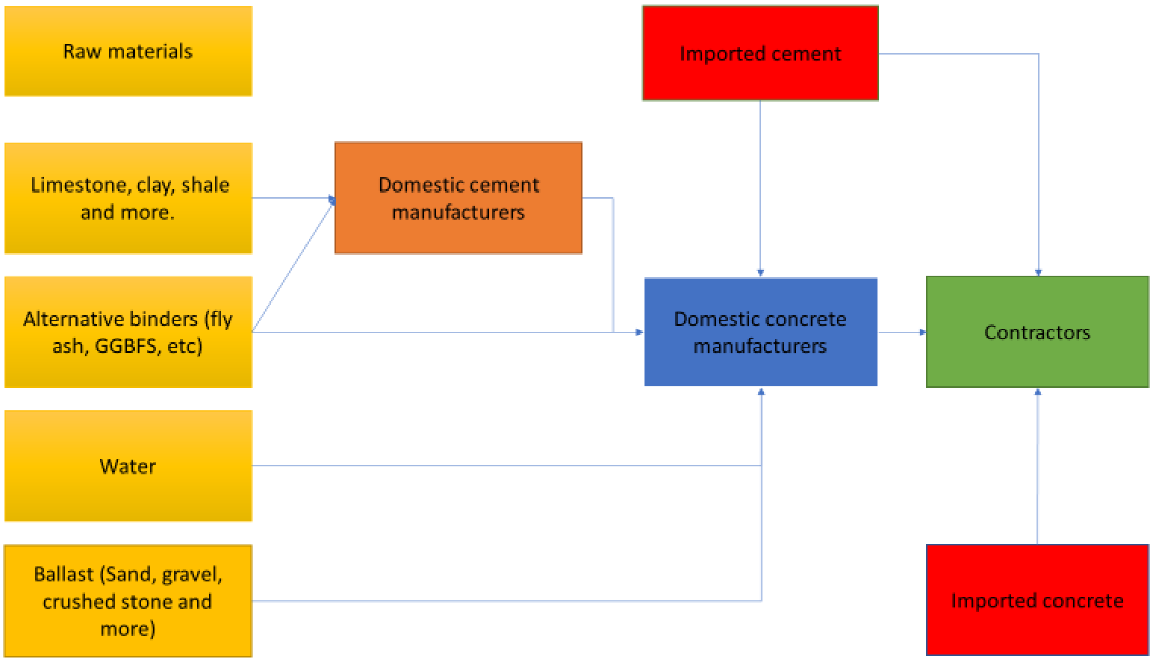


Figure 2. An overview of the cement used in concrete supply chain.

To be able to achieve the emission reduction and reach the Swedish climate target goals of both 2030 and 2045, action needs to be taken today rather than tomorrow. To achieve the goals, there needs to be greater cooperation in between the industries and with researchers to make the current design and construction processes more efficient as well as to increase the speed of technology improvement. Increasing the efficiency of currently used processes is an important step since a lot of the solutions still are in experimental stages and currently too expensive for companies to invest in. However, to be able to find the best solution as quick as possible there is also a strong need of an extensive and quality database within the different industries. Today there is very little data available on the material flows regarding cement and concrete, with public data limited to production and total emission numbers for the entire industries [25]. To be able to do proper analyses on potential for abatement and optimization, more detailed levels of data are needed. Even national data on produced volumes, cement contents in concrete, and weight of cement and concrete seems to be inconclusive, as statistical reports incomplete year on year datasets [13]. Data sufficient to both run analyses on, and perform proper follow ups on, would include how much of each different cement types are used, the average levels of binder content and the concrete composition, together with detailed splits regarding how much goes to each sector for the end use of cement and concrete. An argument used against publishing more data from the producers themselves is that this data is competitive and could give their opponents advantages. However, if only reporting average values, this issue could be avoided. This thesis serves to demonstrate what could be achieved if data gaps were filled, in view of identifying and implementing solutions, and monitor progress which would make the climate goals of 2030 and 2045 possible to achieve. The next sections give a more detailed picture of cement and concrete and the potential abatement measures in focus.

2. Cement

The production of cement is done in three main steps; it starts out with grinding the raw materials into a powder, which is sent into a preheating station. After this step, precalcination takes place, which is where limestone is heated up and turned into quicklime (releasing CO_2). The clinker is subsequently produced in a rotating kiln where the grounded lime from the precalciner is mixed together with clay or shale at a temperature of 1450 °C [14]. Figure 3 contains a schematic image of a cement manufacturing site and the process steps required.

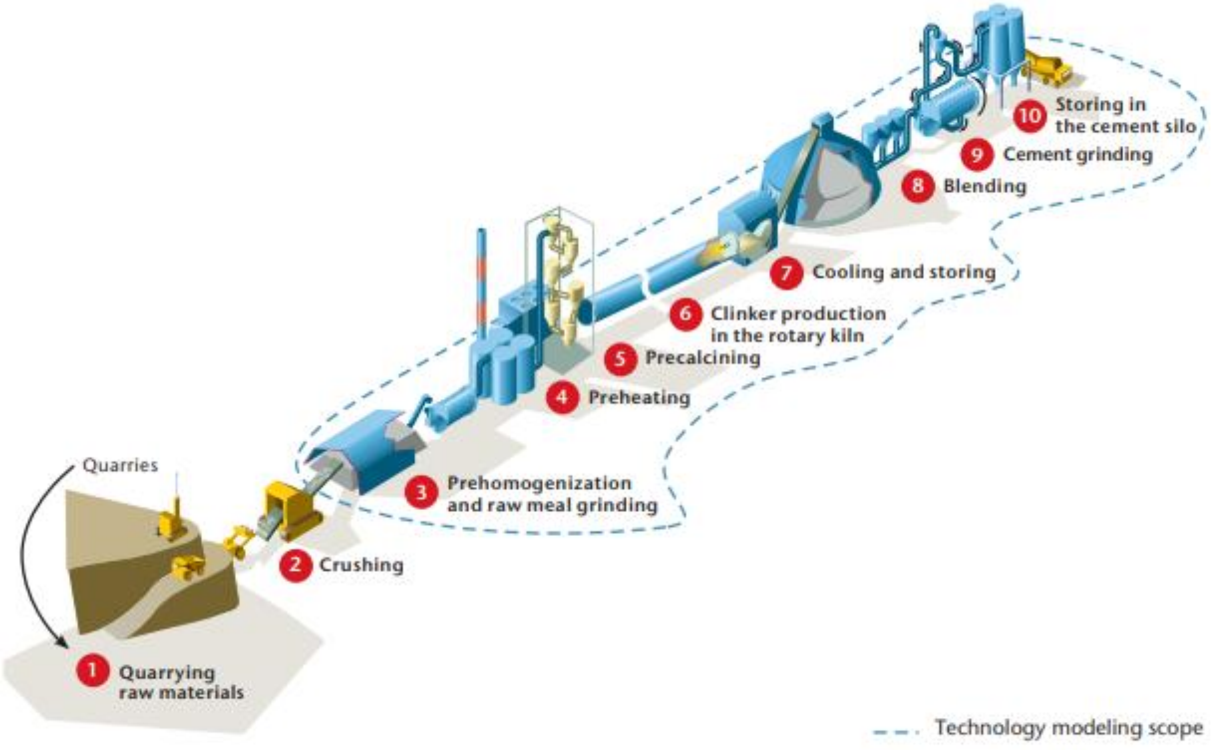


Figure 3 Schematic image of a cement manufacturing plant. Source: IEA “Technology roadmap, Low carbon transition in the cement industry” [14].

Once the clinker has been produced from the kiln it is cooled and then grinded down once again to be mixed with other components such as gypsum and other minerals. Each type of cement composition can be unique, all depending on the properties that is desired from the cement when used in a specific type of product. The most common type of cement today is the Ordinary Portland Cement (OPC), which has a high share of cement clinker and therefore a high climate impact [14]. In efforts to reduce the climate impact other additives that has similar binding properties can be added to the cement to reduce the climate impact. These additives are commonly labelled as SCMs and they have various sources, both natural or as by-products from other industries.

2.1 SCM overview

SCMs, or supplementary cementitious materials (SCMs), as they are also known by, provide one measure to reduce the climate impact of cement. However, there are potential downsides as adding SCMs can affect the properties of the end use product such as the setting time and durability. Therefore, detailed planning is needed when creating the cements and composing the concretes or other end use products to ensure the quality standards that is needed for various construction projects. This chapter will give an overview of the most common SCMs and their origins.

Fly ash is obtained as a by-product from coal power plants, where the fly ash is extracted from the unburnt residues from the coal combustion. The unburnt residues are carried away from the burning zone in the boiler with the flue gases. The fly ash is separated from the flue gases through either electrostatic separation or mechanical separation [26]. The main drawback from increasing the share of fly ash in the cement is that it affects the setting time and therefore a slower strength development in the concrete. It can also be weaker in environments that are exposed to frost, salts and where the possibility for carbonation exists [26]. Sweden has a very small share of the produced fly ash in the EU, where it roughly stands for 0.06% of the total production, thus needing to import fly ash [17].

GGBFS has its origins from the steel industry and the blast furnaces that are used for iron smelting. This process contains mixing iron ore, coke and limestone at temperatures around 1500 °C. While the iron ore is reduced to pure iron, the other materials form a ferrous molten slag on top of the iron. The molten slag is tapped of periodically and if the end goal is to produce GGBFS it must be rapidly cooled. Once the cooling is complete the granules are dried and crushed into a fine powder [27]. The advantages of using GGBFS is increased levels of long-term strength and higher resistance to chemical aggression compared to fly ash. GGBFS however also imply increased setting times [16][27]. The availability of GGBFS depends on the locations of the blast furnaces and as can be seen in Figure 4, they not equally distributed over Europe. This means that if the use of GGBFS is expected to be increased, imports would be necessary. In addition to this Europe is already using approximately 80% of the supplies already [8]. However, Sweden has a higher production share of GGBFS of roughly 3.7% in the EU [17].

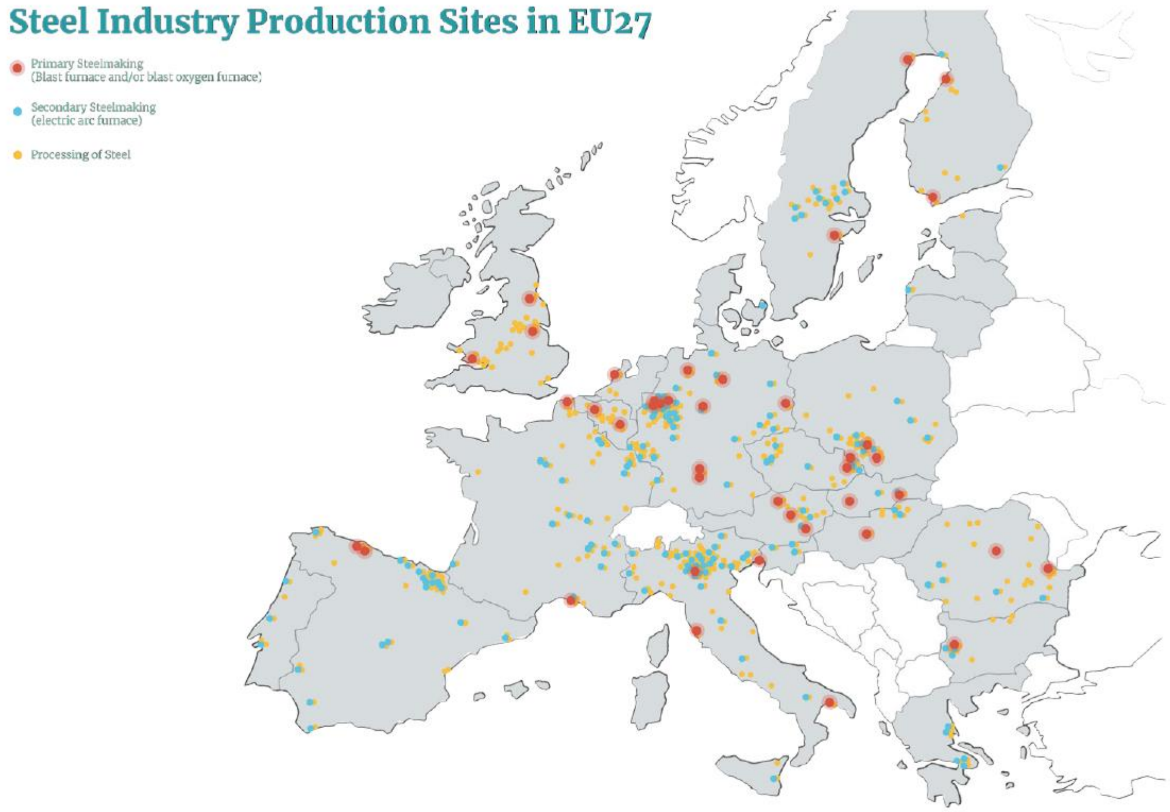


Figure 4 A map of blast furnace locations in Europe. Source: Favier et al (2018) [8].

Other SCMs are pozzolans, which consist of a wide range of volcanic ashes and clays that can be found in many places. However, all pozzolans cannot be used as SCMs. The best types of pozzolans to use as SCMs in cement are pyroclastic materials which have their origin from volcanic eruptions. These are common in countries such as Italy, Germany, Greece and China. Considering that there are many natural reserves of these natural pozzolans and the supply of industrial SCMs are dwindling, there can be an expected increase of usage of these [16]. There are also useful clays that can be used as SCMs although these often require a thermal or mechanical activation treatment to obtain its binding properties. In Figure 5, there is a map overview where usable clays have been marked. Although these exist in many places, to date they are less economically attractive compared to fly ash and GGBFS [8]. This will probably change since Europe is already using all existing supplies of fly ash and GGBFS and the demand is increasing [8].

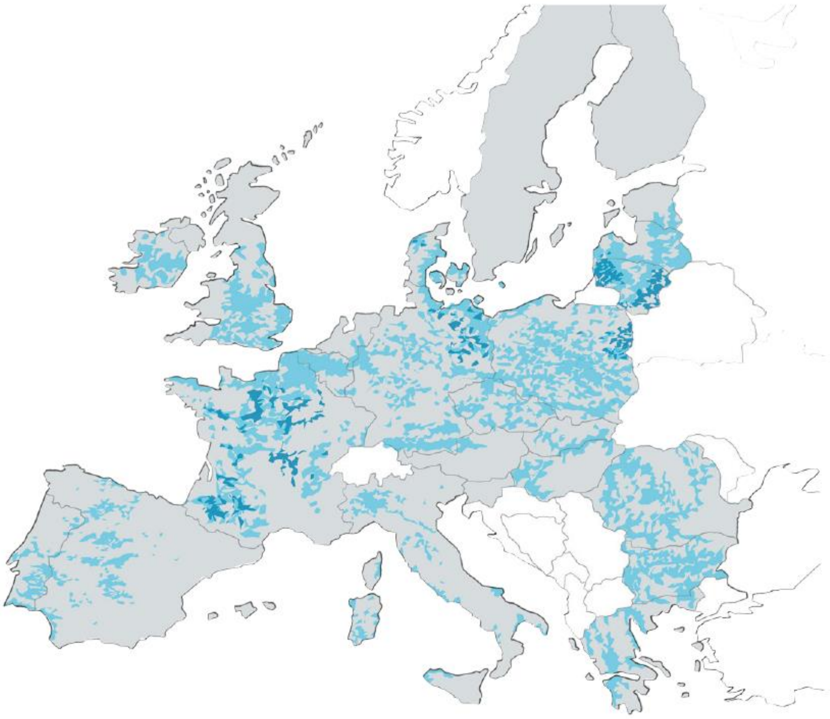


Figure 5 A map of the countries within EU where suitable clays for SCMs are located. Source: Favier et al (2018) [8].

2.2 Cement types

There is a certain type of classification for different cement types in the EU according to the European standard EN 197-1, which contains composition, specifications and conformity for the 27 different types of common cements. These are divided into the categories of CEM I-V with subcategories. The classifications are done regarding to the contents of the cement exists on a percentage base, as shown in **Fel! Ogiltig självreferens i bokmärke.** [28]. The smaller components in **Fel! Ogiltig självreferens i bokmärke.** refers to inorganic mineral materials that are either added to the cement or obtained in the process of making the clinker. The additions of this type can be inert, possess weak hydraulic properties or pozzolanic properties. However, the additions should not increase the water demand of the cement in any higher proportions [28].

Table 1 Simplified overview of the different cement types.

Cement type	Cement clinker (%)	SCM (%)	Minor additional constituents (%)
CEM I	95-100	0	0-5
CEM II	65-94	6-35	0-5
CEM III	35-64	36-65	0-5
CEM IV	45-89	11-55	0-5
CEM V	20-64	36-80	0-5

OPC is often referred to as CEM I, which is the classic cement with the highest amount of cement clinker content. Common usage areas for CEM I in Sweden these days are harsh environments where the risk of exposure to salts and carbonation can occur, such as in coastal areas or on roads. Because of the exposure, it is more difficult to replace the cement in these concrete structures.

As can be seen in Figure 6, the most common type of cement in Europe today is CEM II. This type of cement is the most varied since it contains a low-medium share of SCMs, while also maintaining a high share of cement clinker, therefore having similar properties to CEM I. Many different types of binders are used for CEM II, including fly ashes, GGBFS, limestone and pozzolans. CEM II is widely used where there are no special requirements regarding environmental exposures.

CEM III is more commonly known as slag cement since the only SCM allowed in this category is GGBFS. CEM III allows for a higher share of clinker substitution since the only real drawback is increased setting time (as described in the section about GGBFS). The usage of CEM III could be higher with increased supply of GGBFS and the slower construction rates resulting from increased setting times. Concrete buildings containing GGBFS based cements typically have a longer lifetime then regular OPC [27].

The pozzolanic cements are classed as CEM IV and have a relatively small use today as can be seen in Figure 6, largely been dependent on regional availability. As mentioned in the section about pozzolanic binders this category will probably see an increased use with an anticipated increased use of calcined clays as SCMs. As shown in Figure 5, a larger share of countries have access to suitable clays for SCM than the amount of countries that have access to volcanic materials [8].

Composite cements are known as CEM V and contains fly ash, GGBFS and pozzolans in various compositions [28]. In the EU there are few nations that allow the use of CEM V, mostly due to the lack of data and due to the fact that strength tests are not as easy to perform since the composition varies greatly [29].

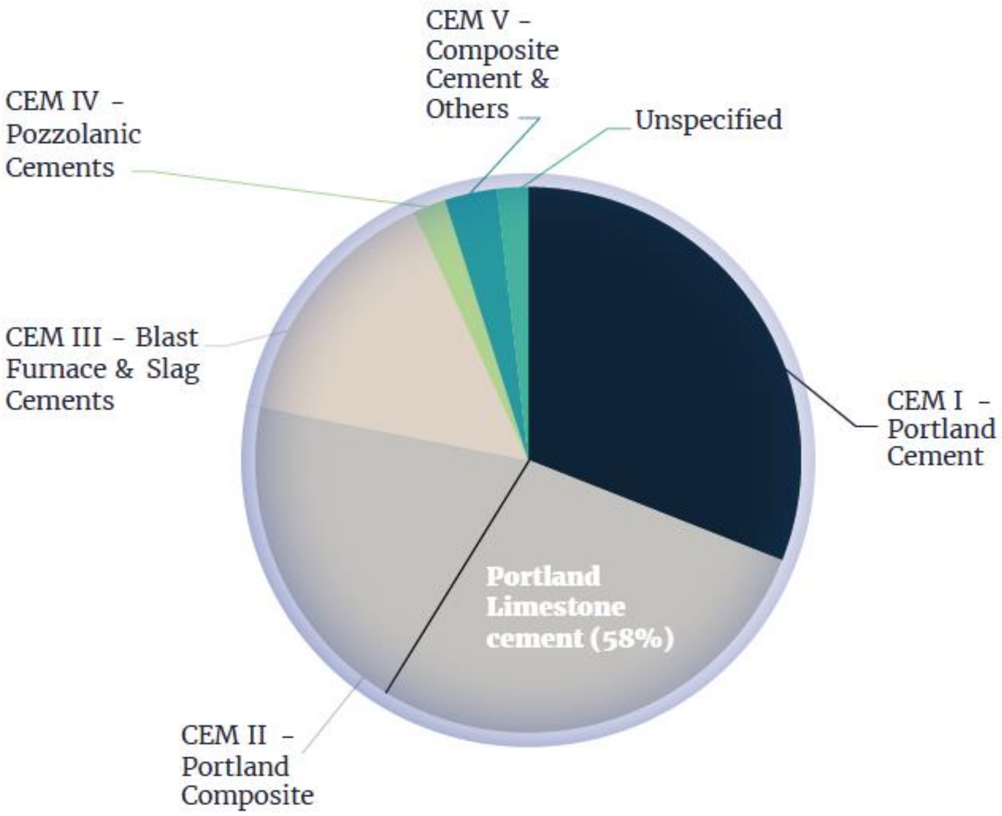


Figure 6 Share of cement types sold in Europe in 2015. Source: Favier et al (2018) [8].

2.3 Cement-based products

Concrete is used in many areas of society, with the largest areas of usage being non-residential buildings, residential buildings and infrastructure [25]. Concrete is also used as smaller building blocks, for example sleepers in railway construction. Figure 6Figure 7 shows the different shares of cement containing products used in Europe 2015, where 76% are different types of concrete.

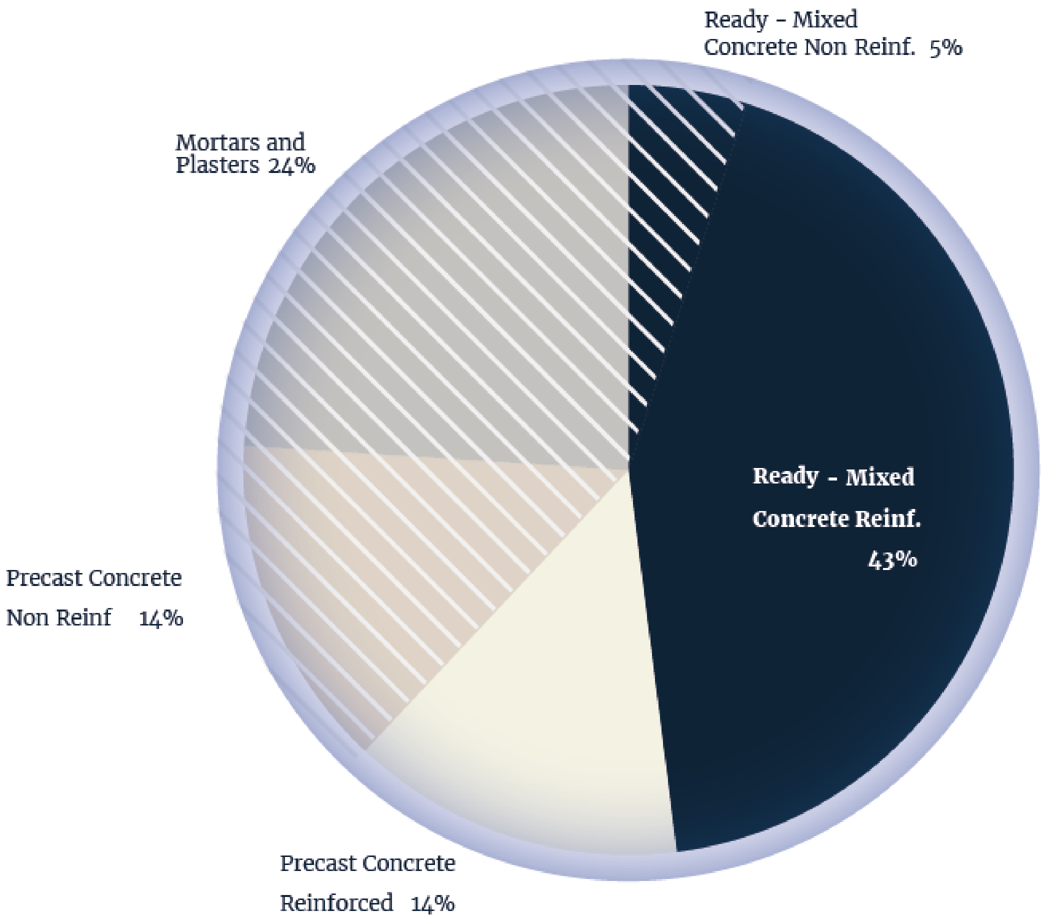


Figure 7 Share of cement used in downstream products in Europe 2015. Source: Cembureau and ERMCO via Favier et al (2018) [8].

Ready-mixed concrete is manufactured in a central plant, while for small batches of concrete or for large jobs where space is limited on the building site, concrete can be mixed on the building site [30]. Precast concrete elements are also made in a centralized plant, where concrete is cast in a mold at a plant to then be transported as one single piece to the construction site [31]. Mortars and plasters are used in the masonry business to bind bricks together or to coat and even the surface on certain walls and concrete flooring. Mortars are also used to repair different structures of concrete, such as cracks on the surface of walls or entirely missing pieces of concrete in structures.

2.4 Exposure classes

Exposure classes is a concept used within the concrete industry to determine which concrete to use based on the environment that is around the construction. As different environments have different exposure to certain chemicals or natural conditions, the exposure class also affect how much cement is used. A common problem that has been identified for the building sector is that engineers typically choose the same exposure class for a broad part of the project to ensure the durability of final structure. However, more careful choices can be made for a project. Walls inside a house for example are not exposed to weather and wind and do not need to withstand the same type of conditions. By having tailormade exposure class choices throughout a construction project, these is thus potential for cement usage to be reduced [8].

The exposure classes are divided into several different categories and subcategories depending on what they are supposed to withstand, e.g. carbonation, corrosion, frost, salt and acidic conditions. In Table 2 Simple overview of exposure classes in the European concrete standard EN-206:2013+A1:2016 [32].Table 2, the different exposure classes according to the European concrete standard EN-206:2013 are displayed [32].

Table 2 Simple overview of exposure classes in the European concrete standard EN-206:2013+A1:2016 [32].

Name of class	**Chemical hazard**	**Typical environment**
X0	None	Concrete inside a building with low humidity.
XC1-4	Corrosion through carbonation.	Concrete that is exposed to water on a regular basis.
XD1-3	Corrosion due to chlorides from other sources then seawater.	Concrete surfaces that is exposed to chlorides from other sources then seawater, such as road salts
XS1-3	Corrosion due to chlorides from seawater.	Constructions close to the coast.
XF1-4	Areas where freezing and thawing repeatedly is common. Includes classes both for when area is exposed to salts or not.	Roads and infrastructure buildings.
XA1-3	Aggressive chemical attacks on the concrete.	Concrete in environment with difficult chemical conditions.

In addition to the problem choosing the correct exposure class, there is a tendency for overspecification of cement within the exposure classes. There is often 20% more cement in the concrete mix than what is required by the standard, for extra safety, to reduce error margins or reduce the risk of uncontrolled extra water to the construction site. To give an example of this, Figure 8 shows the standard for some exposure classes in Austria compared to the actual cement contents.

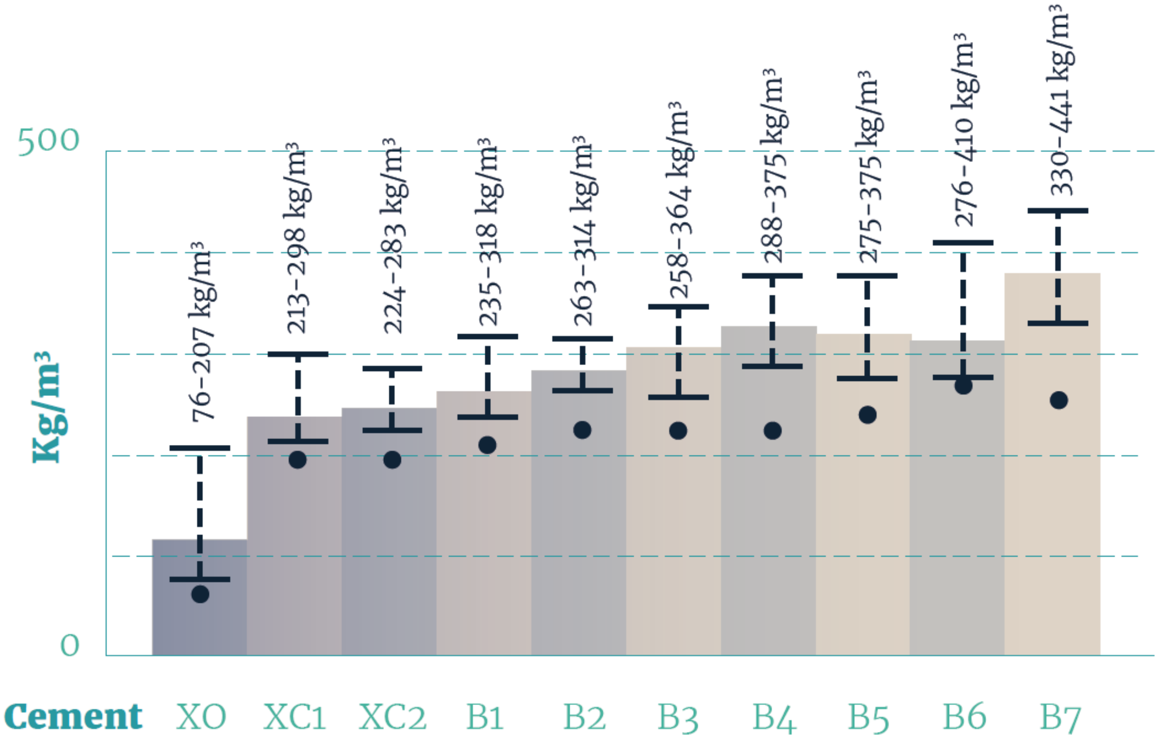


Figure 8 A chart over different exposure classes and their cement content according to Austria standards along with typical amount of cement used. Source: Favier et al (2018) [8].

The black dots in this chart represent the minimum allowed limit of cement per cubic meter concrete, while the bar charts represent the average amounts of cement per cubic meter that is used with the stretched-out lines denoting the range [8]. As can be seen in the chart, there is typically a heavy overconsumption of cement regarding minimum allowed. The level of data to construct a diagram of this type is very detailed and shows that Austria is doing a good job in collecting statistical data regarding the concrete industry.

2.5 Strength classes

Exposure class is not the only factor that decides the amount of cement used in concrete. Strength classes exist within the concrete industry to make sure that the concrete can handle the pressure it has to withstand. The strength classes are written as C12/15 where the first number is for the characteristic cylinder strength in MPa and the second number stands for the cube strength in MPa [33].

2.6 Water to cement ratio and setting time

The amount of water used is an important aspect of concrete as well. The water to cement ratio (w/c) is the ratio between water and cement in concrete, and the exposure classes also decide the maximum allowed w/c. The w/c also gives an indication on the porosity of the concrete [34].

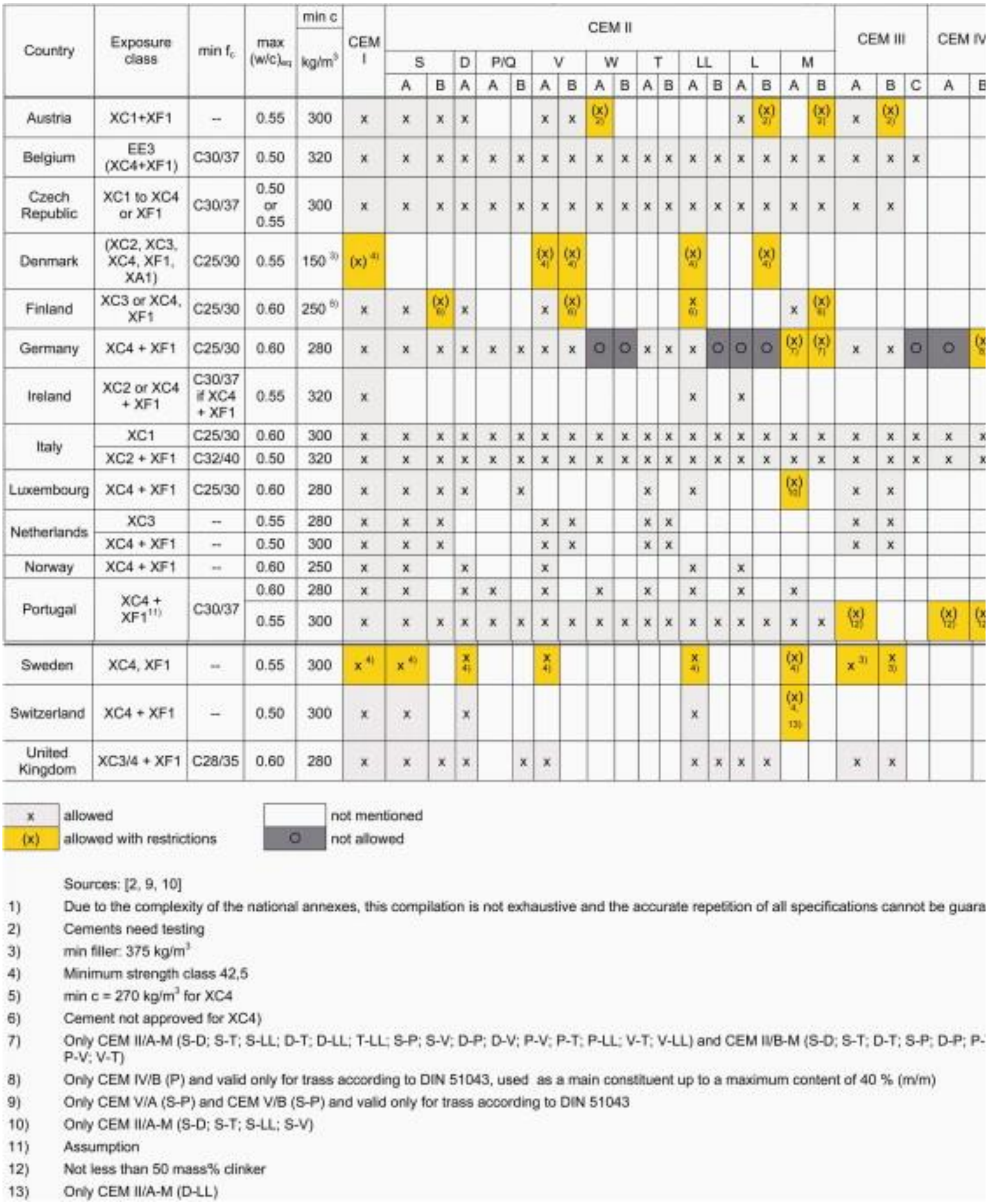
Additional water outside of the chemical reactions in the cement is necessary to work with the concrete. The excess water must be dried away from the concrete, and since concrete with a higher share of SCMs have a very tight structure this can take a long time. A common way to solve this is by adding more cement, and therefore lowering the w/c to below 0.4 since at those levels after a certain point of time all the water will be consumed in the cement reactions. Particularly for flooring concrete in buildings with floor coverings of non-breathable material such as a plastic flooring or parquet, the amount of cement in the concrete is increased. These types of floors are more common in public buildings since a plastic flooring is for example beneficial where easy cleaning is a requirement, such as schools or a hospital.

The setting time is of importance in the construction business, not only for the fact that the construction is completed faster, but there is also less possibility of external factors such as weather to affect the concrete before it has achieved full strength [33]. As mentioned above the setting time is also affected by the addition of SCMs in the cement. The setting time is also affected by amount of water needed in the concrete.

2.7 Standards and regulations for cement and concrete

Cement and concrete have different standards and regulations in the EU, named EN:197-1 and EN:206-1+A1:2016 respectively. The purpose of these standards is to regulate the usage of these components from a safety and quality perspective [23][28]. However, in addition to these, there are also national regulations set by the authorities in each country regarding concrete. Table 3 displays an overview of the national regulations in various European countries for certain exposure classes, demonstrating that the differences can be quite large.

Table 3 Areas of application of cements which is in line with the European cement standard EN 197-1 in concrete, conforming to the concrete standard of EN 206-1 and various national annexes [19]. Grey areas with crosses indicate that the specific cement type is allowed, while yellow squares indicate cement types allowed with restrictions. White squares indicate cement classes and subclasses that are not mentioned in the national regulations or standards.



Country	Exposure class	min f_c	max $(w/c)_{eq}$	min c kg/m³	CEM I	CEM II																	CEM III			CEM IV	
						S		D	P/Q		V		W		T		LL		L		M						
						A	B	A	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	C	A	B
Austria	XC1+XF1	--	0.55	300	x	x	x	x			x	x	(x) 2)						x	(x) 2)		(x) 2)	x	(x) 2)			
Belgium	EE3 (XC4+XF1)	C30/37	0.50	320	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Czech Republic	XC1 to XC4 or XF1	C30/37	0.50 or 0.55	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			
Denmark	(XC2, XC3, XC4, XF1, XA1)	C25/30	0.55	150 $^{3)}$	(x) $^{4)}$						(x) 4)	(x) 4)					(x) 4)			(x) 4)							
Finland	XC3 or XC4, XF1	C25/30	0.60	250 $^{5)}$	x	x	(x) 6)	x			x	(x) 6)					x 6)				x	(x) 6)					
Germany	XC4 + XF1	C25/30	0.60	280	x	x	x	x	x	x	x	x	O	O	x	x	x	O	O	O	(x) 7)	(x) 7)	x	x	O	O	(x
Ireland	XC2 or XC4 + XF1	C30/37 if XC4 + XF1	0.55	320	x												x		x								
Italy	XC1	C25/30	0.60	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	XC2 + XF1	C32/40	0.50	320	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Luxembourg	XC4 + XF1	C25/30	0.60	280	x	x	x	x		x					x		x				(x) 10)		x	x			
Netherlands	XC3	--	0.55	280	x	x	x				x	x			x	x							x	x			
	XC4 + XF1	--	0.50	300	x	x	x				x	x			x	x							x	x			
Norway	XC4 + XF1	--	0.60	250	x	x		x			x						x		x								
Portugal	XC4 + XF1 $^{11)}$	C30/37	0.60	280	x	x		x	x		x		x		x		x		x		x						
			0.55	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	(x) 12)			(x) 12)	(x
Sweden	XC4, XF1	--	0.55	300	x $^{4)}$	x $^{4)}$		x 4)			x 4)						x 4)				(x) 4)		x $^{3)}$	x 3)			
Switzerland	XC4 + XF1	--	0.50	300	x	x		x									x				(x) 4, 13)						
United Kingdom	XC3/4 + XF1	C28/35	0.60	280	x	x	x	x		x	x						x	x	x	x			x	x			

x	allowed
(x)	allowed with restrictions
	not mentioned
O	not allowed

Sources: [2, 9, 10]

1) Due to the complexity of the national annexes, this compilation is not exhaustive and the accurate repetition of all specifications cannot be guara
2) Cements need testing
3) min filler: 375 kg/m³
4) Minimum strength class 42,5
5) min c = 270 kg/m³ for XC4
6) Cement not approved for XC4)
7) Only CEM II/A-M (S-D; S-T; S-LL; D-T; D-LL; T-LL; S-P; S-V; D-P; D-V; P-V; P-T; P-LL; V-T; V-LL) and CEM II/B-M (S-D; S-T; D-T; S-P; D-P; P-
P-V; V-T)
8) Only CEM IV/B (P) and valid only for trass according to DIN 51043, used as a main constituent up to a maximum content of 40 % (m/m)
9) Only CEM V/A (S-P) and CEM V/B (S-P) and valid only for trass according to DIN 51043
10) Only CEM II/A-M (S-D; S-T; S-LL; S-V)
11) Assumption
12) Not less than 50 mass% clinker
13) Only CEM II/A-M (D-LL)

As can be seen in Table 3 there is a large variation between countries in view of requirement and restrictions around cement classes, cement contents etc. [35]. Some noteworthy observations include Italy being one of few countries allowing pozzolanic cement, which is reasonable with its large local availability of pozzolanic materials [17]. There is also a noticeable difference in the number of cement classes allowed in Sweden compared to other countries. Some countries like Germany and Italy are clearly ahead of the curve, since not only do both countries have a complete set of rules for all the common cement types, but they are also working with CEM IV and CEM V. Alongside those two countries, Portugal is the only country that also has some rules about using these two cement classes.

3. Comparison of estimated future cement production and consumption

The emission reduction goals set by countries or the UN is a good general vision to aim for but to be able to achieve these goals each sector needs to have individual plans. Roadmaps can be defined as a plan that is set within an industry by individual companies, organizations or by the authorities about how to reach certain specified goals and when to achieve them. On a worldwide basis the International Energy Agency (IEA) is a key institution in the development towards a safe and sustainable energy supply. Originally founded to ensure a safe oil supply in the 1970s, it has expanded to energy efficiency, sustainable energy supply and much more. The organization investigates many of the key industries in the world regarding energy efficiency, emission reduction possibilities and future alternatives. For the cement industry there is a roadmap updated as late as 2018 with several goals, and how to achieve them [14].

3.1 IEA Roadmap

The IEA roadmap is based on 2 scenarios, a reference technology scenario (RTS) and a 2° C scenario (2DS). The RTS system is based on what commitment nations currently have towards implementing climate policies, energy consumption trends and developing existing technologies. While this is a more realistic measurement compared to a business as usual scenario, it still would result in an estimated temperature increase of 2.7° Celsius by 2100 and probably keep rising after that point. The 2DS scenario projects a scenario where the probability of staying below the 2° Celsius target is 50%, involving direct emissions reduction by 24% to 2050 compared to 2018 and climate neutrality by 2100. Both scenarios are based on current technologies used or in development.

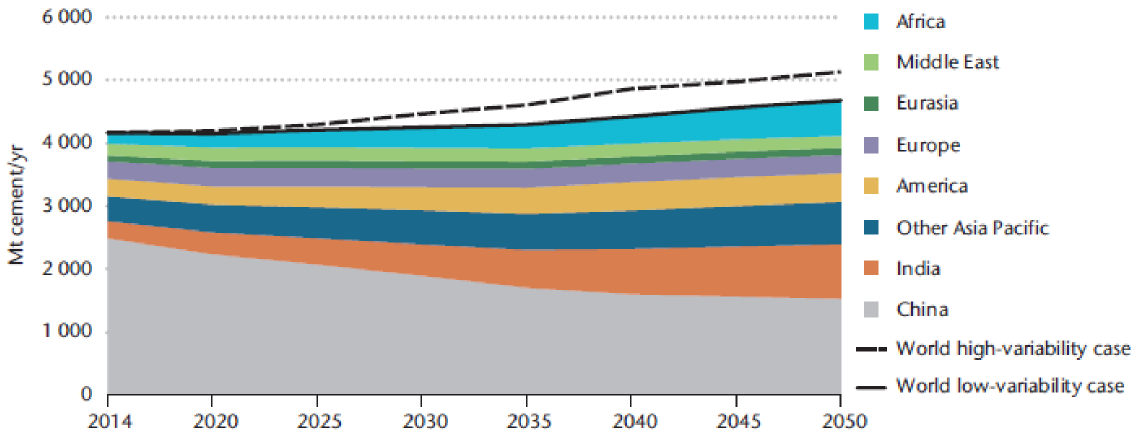


Figure 9 The projected cement production until 2050 in the world. Source: IEA (2018) [14].

As can be seen in Figure 9, the cement production in the world is expected to increase to 2050. While the production in many of the Western countries and China has already stabilized or going down, many developing countries are expected to increase their production drastically where India for example is expected to triple its production until 2050. While reducing the emissions despite an expected production rate is a challenge there are ways to deal with it. Table 4 displays some key figures for both scenarios although the 2DS is the more interesting one, revealing the need for significantly more action then what is currently taken today, as well as in comparison to the projected course in the RTS scenario.

Table 4 Key figures from the IEA roadmap scenario analysis. Source: IEA (2018) [14].

		RTS			**2DS**		
	2014	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Cement production (Mt/yr)	4171	4250	4429	4682	4250	4429	4682
Clinker to cement ratio	0.65	0.66	0.67	0.66	0.64	0.63	0.6
Thermal energy intensity of clinker (GJ/t clinker)	3.5	3.4	3.3	3.2	3.3	3.2	3.1
Electricity intensity of cement (kWh/t cement)	91	89	86	82	87	83	79
Alternative fuel usage (% of thermal energy)	5.6	10.9	14.4	17.5	17.5	25.1	30
Captured CO_2 (Mt/yr)	-	7	65	83	14	173	552
Direct process CO_2 intensity of cement (tCO_2/t cement)	0.34	0.34	0.34	0.33	0.33	0.3	0.24
Direct energy related CO_2 intensity of cement (tCO_2/t cement)	0.2	0.19	0.18	0.17	0.19	0.16	0.13

A common target is climate neutrality by 2045 or 2050, why it is worth noticing that the IEA report sets the climate neutral target to 2100. The IEA report also describes another scenario called Beyond the 2° Celsius target (B2DS), based on climate targets of the world having been set to more ambitious levels in more recent years. From the 2° Celsius target in the 2DS scenario, the ambition in the B2DS scenario is set to well below 2° Celsius and making efforts towards 1,5° Celsius. Nonetheless, the report stresses the difficulties of achieving emission reductions even in line with the 2DS scenario highlighting aspects such as access to renewable fuels for the kilns, low ambition levels in policies and slow technology development of CCS [14]. It is stated that these aspects make the possibilities for the cement and concrete industry to achieve more ambitious goals even harder.

3.2 Swedish roadmaps

The building construction sector is a sector where a lot of concrete is used and the National Board of Housing Building and Planning (Boverket) estimates that about 18% of Swedish CO_2 emission stems from this sector [36]. The Swedish construction and civil engineering sector have in its ‘Roadmap for fossil free competitiveness’ set itself a goal of 50% reduction in CO_2 emissions in 2030 compared to 2015. Until 2022 the goal is that actors within the sector should have mapped their emissions and created climate reduction goals while for 2025, the goal is that a clear emissions reduction trend should be presented [24]. The building construction sector however, does not yet have the same demands when it comes to climate declarations as Trafikverket has, which is the described in the following section. Boverket was given the task by the government in the fall of 2017 to come up with suggestions of how a climate declaration for the construction of a building should be developed [36]. From this task, the government has of the intention to implement a law of climate declarations for the building sector from the 1st of January 2022 [37].

In Sweden, the Swedish Transport Administration (Trafikverket) has set a goal to have climate neutral infrastructure by 2045. To achieve this goal, the authority has set intermediary goals of 15% reduction in 2020 and 30% reduction in 2025 compared to 2015 levels. Even if construction of transport infrastructure contains more emission sources then just cement and concrete, they account for 43% of the total emissions, as demonstrated in Figure 10.

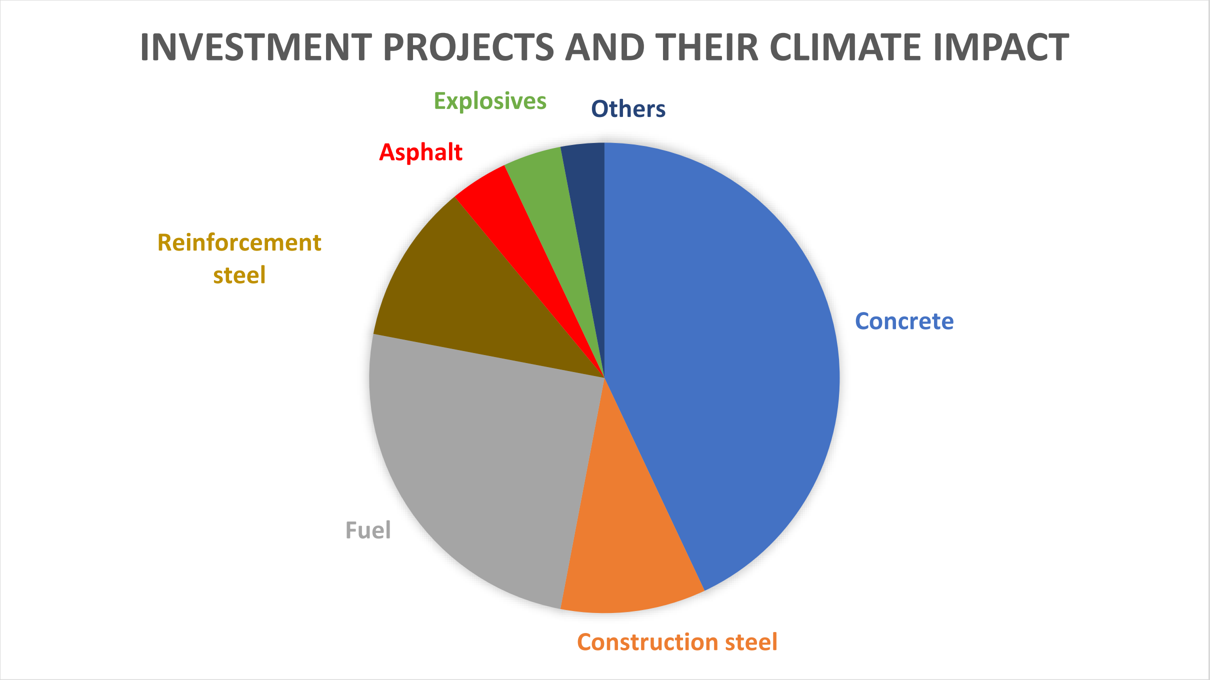


Figure 10 Climate impact associated with construction of transport infrastructure. Source: Trafikverket (2018) [38].

The Swedish Transport Administration puts several demands on future projects as to reach the overall emission reduction goals. For projects over 50 million SEK, there are associated climate targets and mandatory to provide environmental product declarations (EPDs) of individual materials used in the project, along with requirements for a final climate declaration of the project to show that the demands in the contract have been achieved. Financial bonuses can be awarded in the contract. If the required climate impact reductions are not met the contractor will receive a fine [38]. Specific material requirements are also assigned to projects below 50 million SEK, as shown in Table 5.

Table 5 Specific material climate impact requirements for smaller infrastructure construction projects under 50 million SEK for the next decade. Source: Trafikverket and Svensk Betong (2018) [38][39].

	Average value of cement (2018)	**2020–2024**	**2025–2029**
Cement	0.88 kg CO_2 eq/kg cement	≤0.7 kg CO_2 eq/kg cement	≤ 0.62 kg CO2 eq/kg cement
Concrete		25% reduction of CO_2 eq, shown through EPD Type III	35% reduction of CO_2 eq, shown through EPD Type III

3.3 Cementa roadmap

Cementa is as mentioned before the only producer of cement in Sweden. Cementa has presented a roadmap containing the measures depicted in Figure 11 towards reaching climate neutral cements.

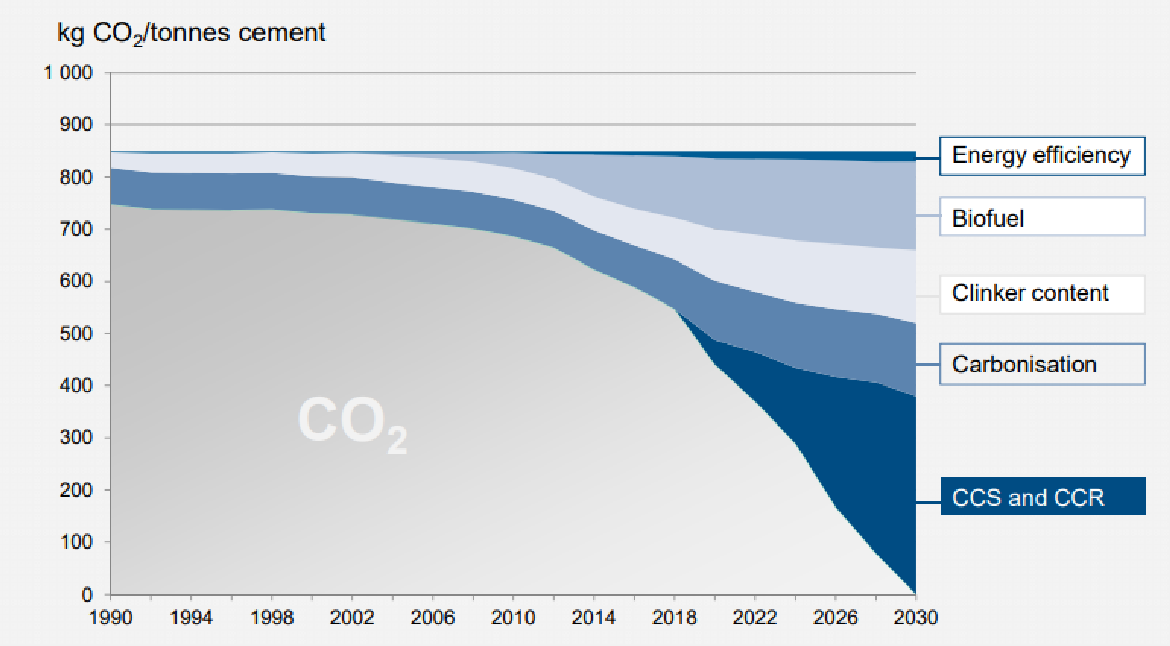


Figure 11 Cementa roadmap for reaching climate neutral cement. Source: Cementa (2018) [40].

As can be seen in Figure 11 most of these suggested changes relies on mitigation outside of the process reaction, including methods such as CCS, change of fuel and carbonation. While Cementa plans to remove a large share of its emissions with CCS as soon as 2030, CCS technologies to date have only been tested in pilot facilities [40]. Investigations done recently have signaled that the prices in the EU ETS system is too low to drive the technology development of CCS forward during the period of 2020-2030 since it is cheaper to buy emission allowances [18]. The roadmap demonstrates a clear request for government support for deployment of CCS. According to the roadmap, a share of 50% alternative fuels was used already in 2016, which means that the potential for future emission reduction from fuel substitution is somewhat limited and there are also supply issues with alternative fuels, including biofuels [40]. In addition to the roadmap, Cementa is pursuing a project called CemZero, which investigates the possibility to replace most of the thermal heat used today for the process with electricity [40]. As Cementa mention themselves this requires not only sufficient amount of green electricity in the market which is a challenge in itself, but also a stable price market for electricity to keep the cement price competitive on the market [40]. While a share of the mitigation is related to new cement products, the roadmap does not specify what these are or in what timeframe these are expected to be on the market. These omissions create uncertainty, particularly combined with the fact that current SCM supply is dwindling and dependent on imports.

4. Data oversight

While the primary focus of the thesis is on the cement and material flow of Sweden, it is still important to compare with data available on a European level and the performance suggested by this data, as to measure where Sweden stands. Further, many of the assumptions relies on a British study [15], why an additional comparison is done for the UK. Many data points would be interesting for this thesis, but to get an overview the list has been narrowed down to a few categories that illustrate basic but vital data. The data points were thus chosen to illustrate differences both in data availability and the levels of performance that different countries have achieved. The comparisons are primarily based on data from the European Ready-Mix Concrete Organization (ERMCO), which distribute statistical report on a yearly basis with a with a high level of detail, along with data from Cembureau (the European Cement Association), ETH Zurich and Shanks et al. [41][8][15].

As previously mentioned, Sweden lacks a lot of current statistical, shown by the date of the most recent data in **Fel! Ogiltig självreferens i bokmärke.** . Sweden is missing data in many categories in the ERMCO reporting since 2012, while the reason for this data gap is unclear. The same trend seems to apply to the reports made by Cembureau, which usually contain more details [41].

Table 6 Data overview of available data describing cement and concrete production and use in Sweden [42][41][18].

Cement data	Sweden			
	Latest data	**Year of latest available data**	**Data for reference year 2015 (if available)**	**Reference**
Total cement consumption	2.8 Mton	2016	2.3 Mton	ERMCO
Domestically produced cement	85%	2016		Swedish Energy Agency
Binder intensity	386 kg/m^3	2012		ERMCO
Cement clinker share	86%	2016	86%	Cementa environmental data
Main SCM	Fly Ash	2012		ERMCO
Cement to ready mix concrete	55%	2012		ERMCO Cembureau
Cement to precast concrete	33%	2012		Cembureau Johnsson, Rootzén 2017
Cement to mortar screed and render	12%	2012		Cembureau

Outdated data make comparisons for a specific year difficult, as well as prohibiting analysis into performance over time. Some additional data on concrete used is available via The Swedish Concrete Association, Svensk Betong, which collects data on the total concrete volume produced domestically along with the split between buildings and infrastructure, as displayed in **Fel! Ogiltig självreferens i bokmärke.**.

Table 7 Data from Svensk Betong regarding domestically produced concrete [25].

Year 2018	**Infrastructure**	**Buildings**
Share of concrete	25%	75%
Volumes (m^3)	1,660,000	4,879,000

For the year 2015, a more detailed split of Swedish concrete use is provided in a report from ETH Zurich, shown in Table 8. The value on infrastructure in this split deviates somewhat from the data from Svensk Betong for the same year which was 24% [25].

Table 8. Data for the share of concrete use in Sweden 2015. Source: Favier et al, 2018 [8].

Category	**Percentage of end use (2015)**
Non-Residential buildings	45%
Residential buildings	23%
Infrastructure	28%
Repair and maintenance	4%

In addition to this, the Swedish Energy Agency stated in a report 2018 that around 15% of the cement used in Sweden is imported [42].

The UK has a higher level of availability when it comes to statistics, which is illustrated in **Fel! Ogiltig självreferens i bokmärke.**. This overview is partly based on a recent detailed analysis on the UK cement flow with the results also displayed in Figure 12.

Table 9 Data overview of available data in the UK [15][41]. *MSR is Mortar, Screed and Render*

Cement data	**UK**			
	Latest data	**Year of latest data**	**Data for reference year 2015 (if available)**	**Reference**
Total cement consumption	9.4 Mton	2016	9.4 Mton	ERMCO Shanks et al, 2019
Domestically produced cement	85%	2014		Shanks et al, 2019
Binder intensity	330 kg/m^3	2012	330kg/m^3	ERMCO Shanks et al, 2019
Cement clinker share			79%	Shanks et al, 2019
Main SCM	GGBFS	2016	GGBFS	ERMCO Shanks et al, 2019
Cement to ready mix concrete	65%	2016	65%	ERMCO Shanks et al, 2019
Cement to precast concrete	22%	2014		Shanks et al, 2019
Cement to MSR	15%	2014		Shanks et al, 2019

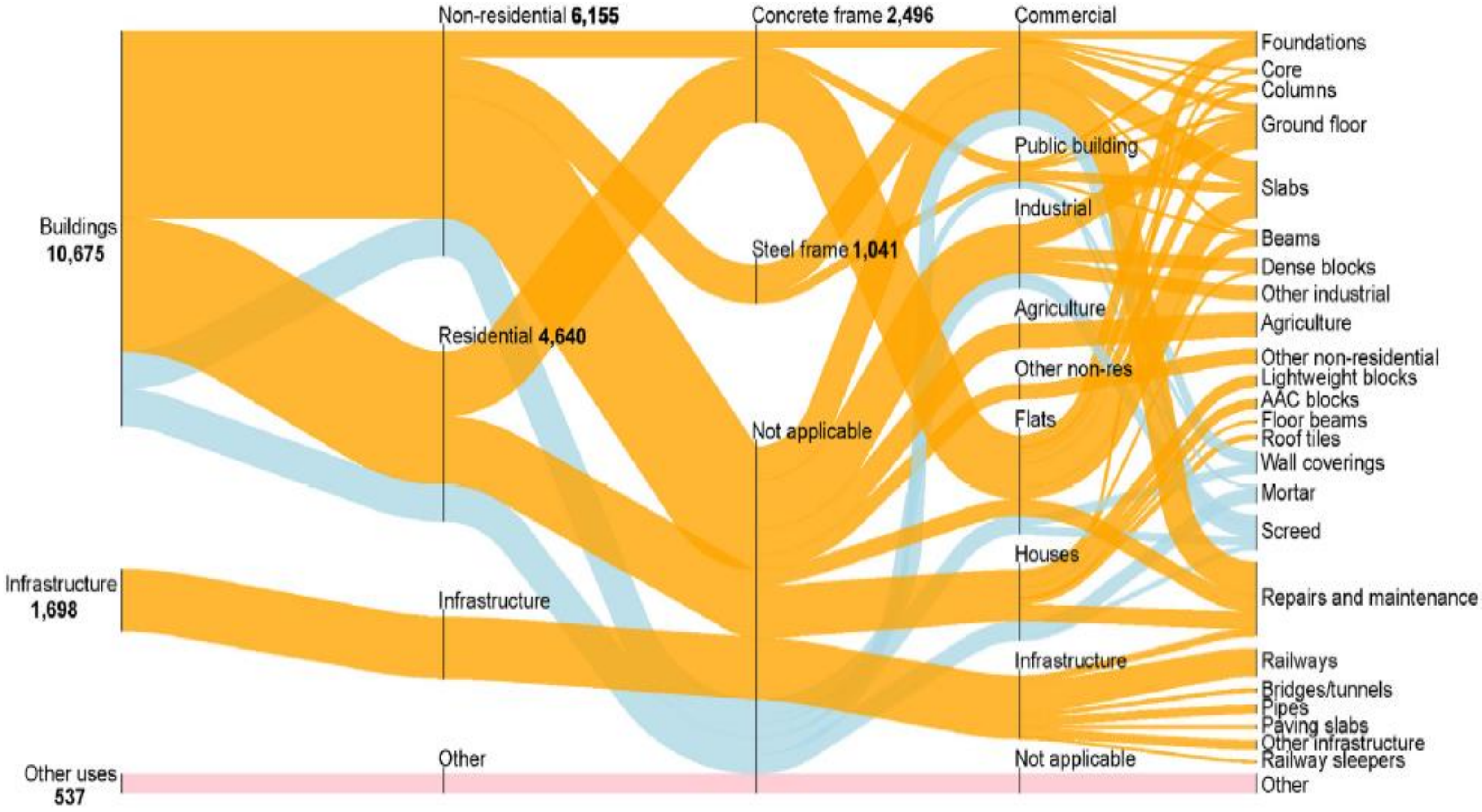


Figure 12 Flowchart of cement in the UK. [15]

Table 10 Data overview of available data describing cement and concrete production and use in the EU. Sources: Favier et al (2018), ERMCO (2019)[8][41].

Cement data	**Europe**			
	Latest data	**Year of latest data**	**Data for reference year 2015 (if available)**	**Reference**
Total cement consumption	129 Mton	2016	129/150/167 Mton*	ERMCO ETH Zurich, 2019 Material Economics, 2019
Binder intensity	317 kg/m^3	2012	317kg/m^3	ERMCO
Cement clinker share	73%	2016	73%	ETH Zurich, 2019
Cement to ready mix concrete	50%	2016	48%	ERMCO ETH Zurich, 2019 Material Economics, 2019
Cement to precast concrete			28%	ETH Zurich, 2019 Material Economics, 2019
Cement to mortar screed and render			24%	ETH Zurich, 2019 Material Economics, 2019

The EU dataset in general much better updated but one can also read from the values of the data that a lot of countries are ahead of Sweden when it comes to environmental performance regarding the cement and concrete. The average for important environmental performance indicators is lower in Europe compared to Sweden, with average binder intensity of 398 kg/m^3 concrete in Sweden compared to 317 kg/m^3 concrete in Europe (20% lower) and an average cement clinker share of 73% in Europe compared to 86% in Sweden.

5. Method

This section describes the procedure of this thesis, starting with a literature overview to gather knowledge about the current status of the market and acquire data. Based on this information a suitable analysis method was chosen, which in this case was material flow analysis. With the limited amount of available data, the estimated provided here relies on several assumptions and approximations. The idea has been to show what kind of analysis work that could be done and accomplished if the industry had good statistical data. Five scenarios were created with different changes to illustrate the potential of emission savings with various methods related to material usage.

5.1 Literature study

The literature study identified the current knowledge level that exists about both end-uses of cement, identifying a large gap in data availability, with limited easily accessible data. This lack of data precluded a detailed analysis of the material flows of cement and concrete in Sweden.

The focus of the literature study thus shifted towards other data sources and studies done on an international level to see if there was any available data or similar studies done for other countries.

Obtaining an overview of the cement flow through the society is a prerequisite to succeed in the project of illustrating potential emissions savings from abatement measures linked to the material flow. A detailed material flow provides the ability to pinpoint how much specific changes in every area of the end use of cement affects the emissions from the industry. While the lack of data has precluded the conduction of a comprehensive current analysis from product to end use of cement flow in Sweden, the data that has been retrieved on the domestic as well as international level, enables the creation of an approximate material flow of cementitious materials in Sweden. This breakdown was developed by using material flow analysis.

5.2 Material Flow Analysis

Material flow analysis (MFA) is a tool for the measurement and prediction of environmental pressures from the use of materials in an economy [43]. As much detailed data as possible is gathered to do a map of the material flow from raw material to different end use areas. The scope of a MFA is usually confined to a specific geographic region or economy. In this case this method is applied to the flow of cement in Sweden. The method aims to give a system wide understanding and has emerged as the primary methodological framework within flow accounting approaches as it offers the greatest scope of application for environmental accounting and systems analysis.

An important step within material flow analysis is to set the system boundary. In this case it will be based on cement-based products used in Sweden. Imported cement is included in the model, while imported concrete, mortar, screed and renders are excluded from the study due to having no reliable way to estimate this with current publicly available data.

The level of analysis adopted in the model for this study is similar to the one used in a report by Shanks et al., which details the cement material flow in the UK [15]. A map over the material flow is created by combining known data with estimations for the material flow. With the help of different cement types (as described in the next section), it is possible to convert the concrete volume flow into a mass flow for cement and create a map of the mass flow.

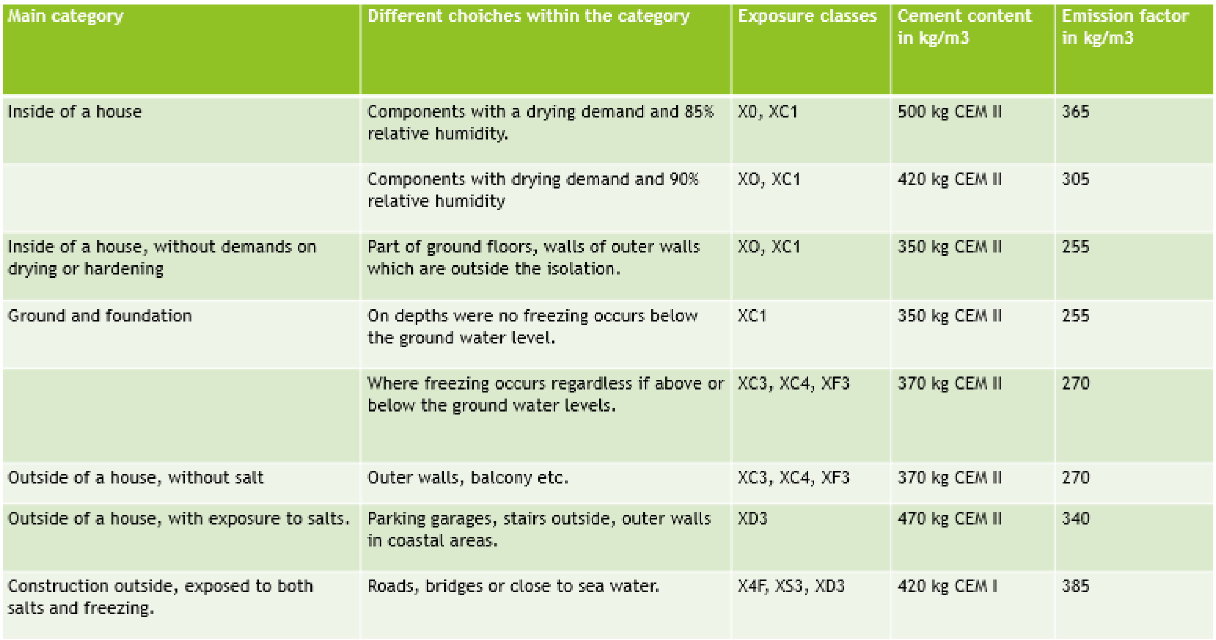
The study focuses on dividing buildings into non-residential and residential buildings followed by a deeper split in the non-residential category to distinguish that there are differences between many of the application areas. While there are of course differences between single- and multi-family housing for residential buildings, most concrete is used in multi-family buildings (in addition to adding another layer of uncertainty, why this is not considered).

5.3 Assumptions and data used

This study uses various methods of approximation to represent current use of cement and concrete using available data and making assumptions to work around them with support of comparisons to the more detailed data that is available for other countries, particularly the UK.

Even though there is a general lack of data, a report written by Svensk Betong gives estimations on standard cement composure for certain building categories, which can be seen in Table 11.

Table 11. Different concrete types used in buildings and roads depending on application. Source: Svensk betong [39].



Main category	Different choiches within the category	Exposure classes	Cement content in kg/m3	Emission factor in kg/m3
Inside of a house	Components with a drying demand and 85% relative humidity.	X0, XC1	500 kg CEM II	365
	Components with drying demand and 90% relative humidity	XO, XC1	420 kg CEM II	305
Inside of a house, without demands on drying or hardening	Part of ground floors, walls of outer walls which are outside the isolation.	XO, XC1	350 kg CEM II	255
Ground and foundation	On depths were no freezing occurs below the ground water level.	XC1	350 kg CEM II	255
	Where freezing occurs regardless if above or below the ground water levels.	XC3, XC4, XF3	370 kg CEM II	270
Outside of a house, without salt	Outer walls, balcony etc.	XC3, XC4, XF3	370 kg CEM II	270
Outside of a house, with exposure to salts.	Parking garages, stairs outside, outer walls in coastal areas.	XD3	470 kg CEM II	340
Construction outside, exposed to both salts and freezing.	Roads, bridges or close to sea water.	X4F, XS3, XD3	420 kg CEM I	385

For the applications using CEM II cements in Table 11, Svensk Betong reports a reference corresponding to a 50-50 mixture of CEM II/A-V and CEM II/A-LL, meaning a combination of fly ash and limestone-based cement. Table 12 displays the assumptions regarding clinker levels for the different cement types.

Table 12 Assumptions made for the cements used to model the current material flow [23][32].

Cement type	**SCM Share**	**Minor additional constituents**	**Chosen levels for this project**
CEM II/A-V	6-20% Fly ash according to EN-197-1.	0-5% allowed according to EN-197-1.	For the CEM II the levels were set to 13% SCMs and 5% smaller components, which means a clinker share of 82%.
CEM II/A-LL	6-20% Limestone according to EN-197-1	0-5% allowed according to EN-197-1.	
CEM I	None allowed.	0-5% allowed according to EN-197-1.	95% clinker and 5% smaller components was chosen for the CEM I.

To be able to use these numbers there is a need for a more detailed approximation regarding the split between infrastructures and buildings for concrete. For this approximation, the study by Shanks et al was used as proxy [15]. While this study is pertain to the UK, it is perceived to be similar enough to use as the main basis for the approximations on the split between concrete for residential and non-residential buildings alongside data published by Favier et al.[8], from which the share of concrete use for repair and maintenance is also sourced. With the numbers from both the Shanks and the Favier report, the approximation for the Swedish cement material flow is set according to **Fel! Hittar inte referenskälla.**Table 13 and Table 14 for the year 2018.

Table 13 Assumed shares for the main categories of concrete use in different applications in Sweden.

Category	**Percent of end use (2018)**
Non-Residential	43
Residential	28
Infrastructure	25
Repair and maintenance	4

Table 14. Assumptions for the split of concrete use for non-residential applications.

Categories	**Subcategories**	**Share (%)**	**Sub share (%)**
Agriculture		14	
Industry		26	
Public Buildings		11	
	Inner Walls		35
	Foundations and slabs		50
	Outer walls, balconies etc.		15
Commercial Buildings		42	
	Inner Walls		35
	Foundations and slabs		50
	Outer walls, balconies etc.		15
Others		7	

Table 15**Fel! Hittar inte referenskälla.** and

Table 16 detail non-residential and residential applications of cement-based products with respective concrete and cement type choices from Table 11, as well as the basis of the assumptions. The subcategories of residential buildings have the same split as subcategories of non-residential buildings according to Table 14**Fel! Hittar inte referenskälla.**.

Table 15 Assumptions for the different categories chosen and which report or data they are based on.

Non-Residential buildings	**Subcategories**	**Concrete type**	**Assumptions based on**
Agriculture		Exposure to salts and aggressive environment, which means a need for resistant concrete.	[15]

Industrial		Exposure to salts and aggressive environment, which means a need for resistant concrete	[15]
Public buildings			[15]
	Inner walls	Inside wall concrete since the exposure to hazards are very small.	[44]
	Foundations and slab	Many public buildings use a plastic mat as floor since the ability to be able to clean easy is required. Therefore, a concrete optimized for a high drying demand is suitable.	[44]
	Outer walls, balcony etc.	Outer walls concrete.	[44]
Commercial buildings			
	Inner walls	Inside wall concrete since the exposure to hazards are very small.	[44]
	Foundations and slab	In this category a mixture of the two different drying demand levels according to Svensk Betong references have been used.	[44]
	Outer walls, balcony etc.	Outer walls concrete.	[44]
Other			[15]

Table 16 Assumptions for the different categories chosen and which report or data they are based on.

	Subcategories	Cement type	Assumptions based on
Residential buildings			[15]
	Inner walls	Inside wall concrete since the exposure to hazards are very small.	[44]
	Foundations and slab	The level of drying demands is reduced further compared to non-residential buildings, which means that mostly the flooring concrete with lower drying demand is used.	[44]
	Outer walls, balcony etc.	Outer walls concrete.	[44]
Infrastructure		Construction concrete with construction cement (Cem I).	[39]
Repair and maintenance		Construction concrete considering the external use and exposure of many repairs.	[15][8]

5.4 Approximation model

The aim of the approximation model is to establish data from various different subcategories as listed in **Fel! Hittar inte referenskälla.** and **Fel! Hittar inte referenskälla.** to see how much each category is contributing to the total cement flow in Swedish society to enable the extraction of representative parameters, which can be compared with available data. Five parameters are extracted as listed in Table 17, with their calculation and implication described in detail in the next section.

Table 17 The parameters of interest to obtain from the approximation of the cement flow.

Parameter	Unit
Total binder flow (in concrete)	kt
Total binder flow	kt
Total cement clinker flow (in concrete)	kt
Total emissions	kt
Average binder content	kg/m^3
Average clinker content	%

Total binder flow in concrete: Cement clinker plus other binders such as fly ash, limestone and GGBFS in concrete applications. Equation 1 describes how this values are calculated. The values for the concrete volumes is taken from Table 7 combined with the respective shares from Table 13**Fel! Hittar inte referenskälla.** and Table 14. Binder content values are taken from Table 11 (for the base case scenario).

$$Concrete\ Volume\ (m^3) * Binder\ Content\ \left(\frac{kg}{m^3}\right) = Binder\ Flow\ (kg)\ (1)$$

Total binder flow: Same as above but with inclusion of mortar, screen and renders. Calculated in the same way as Equation 1 but adding the non-concrete cement products as well.

Total cement clinker flow in concrete: Amount of cement clinker in concrete. This value is calculated in a very similar way as the binder flow, using the clinker content instead of the total binder content. The clinker content for the base case is calculated from the assumptions made in Table 15**Fel! Hittar inte referenskälla.** multiplied with the binder content values in Table 11.

$$Concrete\ Volume\ (m^3) * Clinker\ Content\ \left(\frac{kg}{m^3}\right) = Clinker\ Flow\ (kg)\ (2)$$

Total emissions: Calculated according to Equation 3 based on the emission factors listed in Table 11 and the concrete volume for each application.

$$Concrete\ Volume\ (m^3) * Emission\ Factor\ \left(\frac{kg}{m^3}\right) = Emissions\ (kg)\ (3)$$

Average binder content in concrete: Average amount of binder (cement clinker plus other binders such as fly ash, limestone and GGBFS) per m^3 concrete. The average binder content is calculated from the total binder flow divided by the total concrete volume in Table 7.

$$\frac{Binder\ Flow\ (kg)}{Concrete\ Volume\ (m^3)} = Average\ Binder\ Content\ \left(\frac{kg}{m^3}\right)\ (4)$$

Average clinker share in concrete: Average content cement clinker in concrete. This value is calculated from the result in the respective scenarios listed in the chapter below.

$$\frac{Clinker\ Flow\ (kg)}{Binder\ Flow\ (kg)} = Average\ clinker\ content\ (\%)\ (5)$$

5.5 Scenarios

The goal of the thesis is to present a constructed map of the material flow and alongside that show the effects of different implementations of emissions abatement measures within the use of cement. Scenario analysis is a tool used among others to determine expected ranges of emission reduction of any given management option [45]. Therefore a few different scenarios are constructed within this study to show the effects that certain changes have on overall numbers, such as cement use and emissions. All scenarios are constructed from the perspective of material substitution and what could be made with alternatives that exists today. This means that all the scenarios have the same volumes of end use products.

For scenarios other than the base case, different types of cement products have been used as references. Some are existing products and others are theoretical values in cases where an improved product compared to the base case does not exist on the market. The shortenings in the parenthesis next to the scenario names are the shortened versions to fit in the result diagrams.

5.5.1 Scenario 1 – Base case

This case is the construction of the flow map as per the approximated cement use in Swedish society today, calculated with the data and assumptions described in the previous section using the cement values and types described as references by Svensk Betong as per Table 11.

5.5.2 Scenario 2 – Reduced drying demand (Small change)

A high pace of construction in Sweden have led to highly set drying requirements for certain applications, particularly flooring. This implies a use of concretes with a high cement content. This scenario explores what a single change in one of the major categories can do for overall material use and associated emissions. The scenario adopts a reduction in drying demand for slab and foundations concrete from a requirement of 85% to 90% relative humidity, which replaces the concrete types in the base case with concretes with lower binder intensity for interior applications.

5.5.3 Scenario 3 – Reduced binder intensity (Red bind)

This scenario adopts an optimization of the level of binders used in the cement-based products across all end-use applications. This approach means that the same cement type that is currently modelled in the base case is used, while the overall amount of cement used is reduced. Compared to Scenario 1, this scenario is using concrete with the lowest binder intensity found on the market combined with estimations in the report from Favier et al [8].

5.5.4 Scenario 4 – Using CEM II with a higher SCM share (CEM II)

According to Svensk Betong, many areas of application use cements with SCMs (CEM II) already today. However, as is shown in the section about different cement types there are a lot of variations for CEM II. This scenario shows the effects of using versions of CEM II with a higher level of SCMs across all end-use applications.

5.5.5 Scenario 5 – Application of CEM III (CEM III)

As shown in the cement type section (cf. Table 1), CEM III has higher share of SCMs compared to CEM II. This scenario keeps the same binder intensity as the base case but explores the effects of increasing the share of SCMs. While this scenario might not be fully realistic in practical application, it shows the potential effect of SCMs alone.

5.5.6 Scenario 6 – Current best in practice (BIP)

For this scenario the market has been viewed for different types of cement products that exists today and put together the best possible combination of existing products. In the areas where newer improved cement sorts are not available, various reports have been studied to find what numbers could be realistic in the relatively close future.

6. Results

6.1 Validation of base case

To validate the approximation of current cement flow, a comparison was made with the latest available data presented by Cementa and ERMCO (2016 data). Although the approximation model was based on 2018 years values, concrete volumes are adjusted to account for this variation. Table 18 displays the values used for the validation.

*Table 18 Comparison between official production statistics from Cementa, ERMCO statistics and the approximation model estimates. *The binder content comparison values from ERMCO is from the year 2012* [41][46][47].

Year 2016	**Total cement use (kt/year)**	**CO_2 Emissions (kt/year)**	**Clinker share (%)**	**Binder Content (kg/m^3)**
Cementa Environmental data	2500	2100	86	-
ERMCO Statistics 2016	2800	-	-	398*
Approximation model	2829	1975	86	422
Boverket/Naturvårdsverket (2019)	-	-	-	420

The difference between the cement use in the approximation model and the Cementa production is explained by the fact that several concrete manufacturers also use imported cement in their production, accounting for around 15% of cement use in 2018 according to the Swedish Energy Agency [42]. The similarity between approximation model and the ERMCO statistics would point to the overall cement flow being accurate. In addition, the model seems to work well for approximating the clinker share. The reason for emission levels being lower in the approximation model than according to Cementa figures, can be due to the reference types from Table 11 having lower emission factors (different associated cement types) than the real products used in respective categories, which is also indicated in recent analysis on the emissions status of the Swedish construction industry [47]. One interesting thing to note is both according to a recent report from Boverket and Naturvårdsverket the binder content has gone up since the last data available from the ERMCO statistics from 2012, the approximation model also displayed a very similar number.

6.2 Base case cement flow

The base case scenario is a detailed approximation of the cement flow within the major usage areas. The mass flow of cement within the different categories is presented as a Sankey diagram in Figure 13.

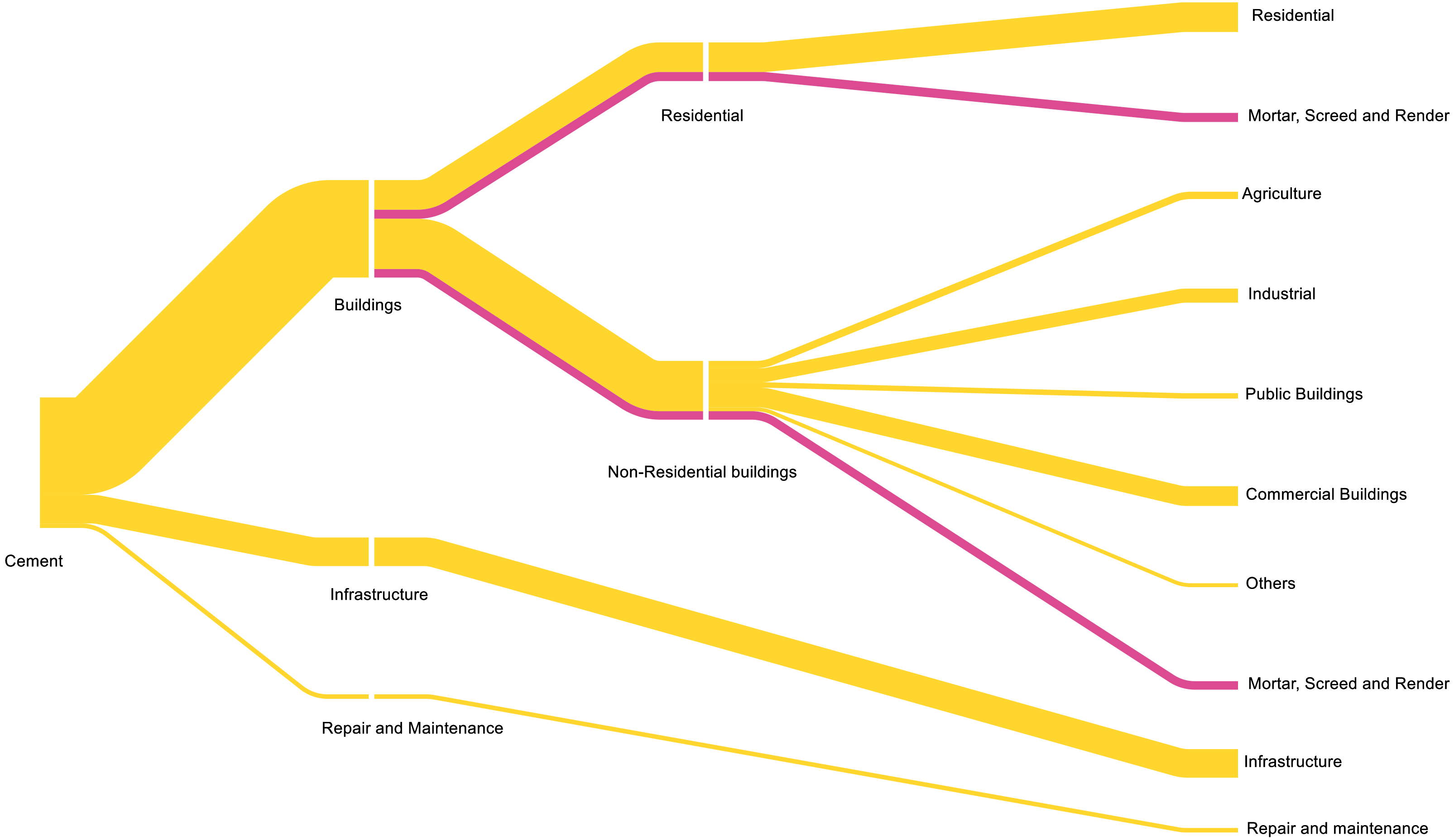


Figure 13 Mass flow of cement in Sweden for the Base case. Yellow lines represent cement that are used in concrete, the pink lines represent non-concrete applications of cement such as mortar, screed and renders.

The Sankey diagram is divided in the four main categories and respective subcategories that were listed in Table 13 and Table 14**Fel! Hittar inte referenskälla.**. The yellow mass flow represents cement that are used in concrete, the pink lines represents non-concrete applications of cement such as mortar, screed and renders. The results for the base case scenario for the parameters described in Table 17 are listed in Table 19.

Table 19 Results from the base case for the year 2018.

Total binder flow (in concrete)	2760	kt
Total binder flow	3187	kt
Total cement clinker flow (in concrete)	2368	kt
Total emissions	2225	kt
Average binder content	422	kg/m^3
Average clinker content	85.8	%

6.3 Scenario comparisons

Figure 14 to Figure 17 exhibit the results of the different scenarios compared to the base case of current material flow.

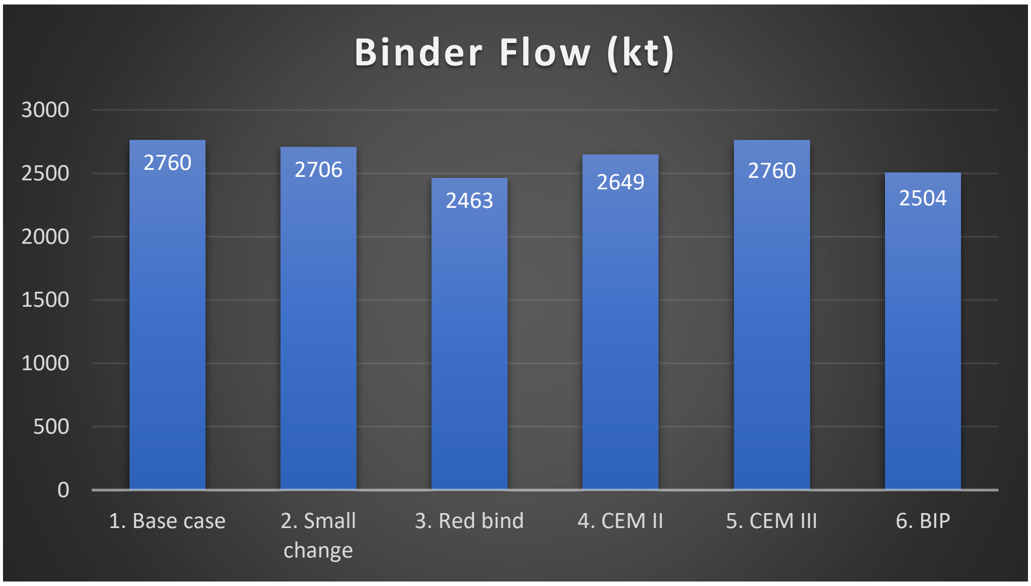


Figure 14. Binder flow data from the scenarios.

As can be seen in the graph, Scenario 3 has the lowest flow of binder produced which is not surprising since reducing the binder intensity was the primary goal of that scenario (11% lower than the base case scenario). Scenario 6 is however not far behind despite only using cement products that currently exist on the market.

The average binder content is also an important aspect in reducing the cement clinker use (and associated emissions), as per Figure 15. Even if Sweden has no recorded data on this indicator since 2012 according to ERMCO statistics, it is still useful to compare the scenarios to the European average of the latest released data [41].

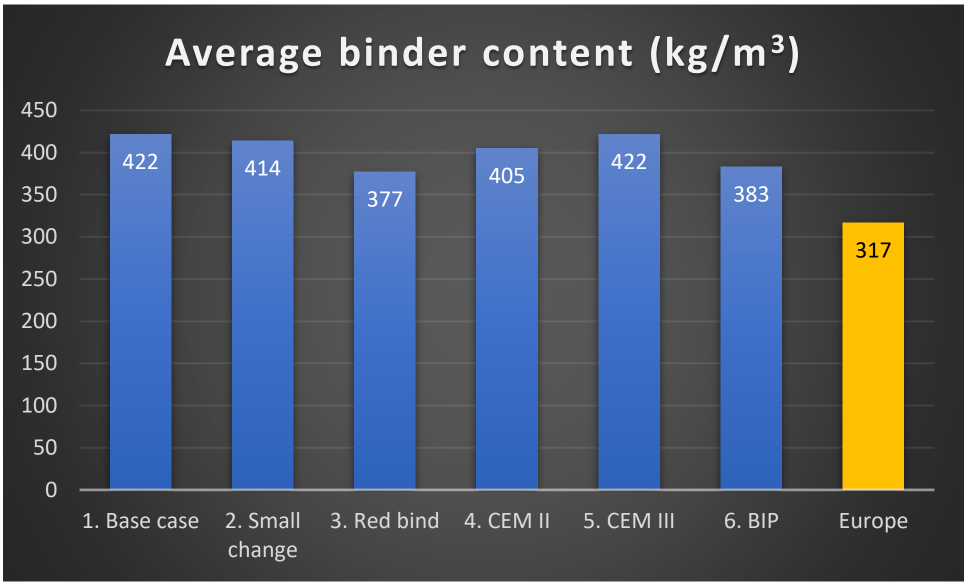


Figure 15 Results for average binder content for scenarios plus comparison with the European average.

Similar trends for the scenarios as for the binder flow are exhibited for the average binder content, which is expected since the average binder content is a function of how much cement is used. Interesting to note here is how much lower the average binder content is in the European average. According to ERMCO the average binder content in 2016 was 317 kg/m^3 which is 16% lower than the binder content estimated for Scenario 3 [41].

Reduction of the clinker share is another way to reduce the emission levels, with the results on clinker share from the different scenarios illustrated in Figure 16.

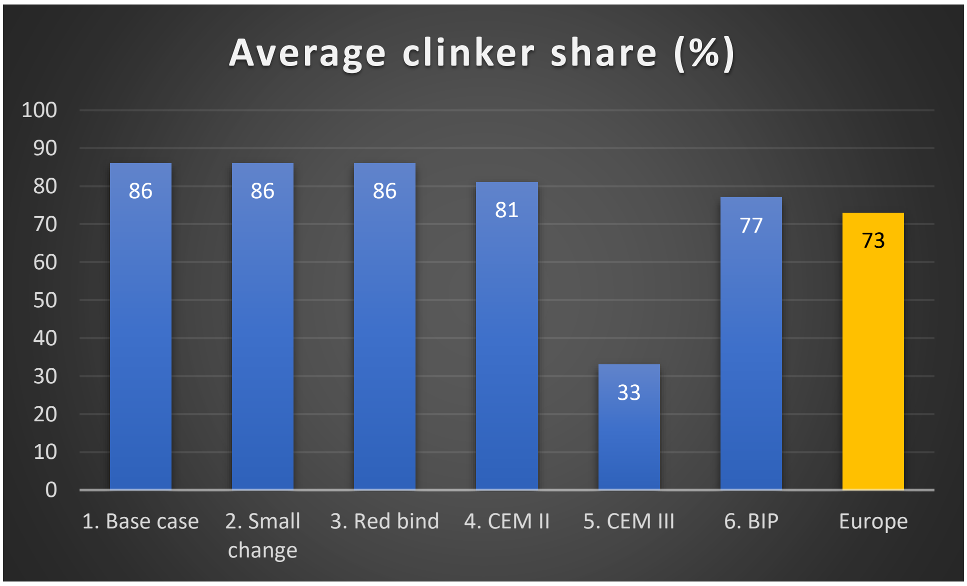


Figure 16 Results for average clinker share for scenarios plus comparison with the European average.

The reason the first 2 scenarios are basically unchanged compared to the base case is that the focus was on reducing the binder intensity in categories rather than changing the type of cement that was used. The other results are as expected, scenario 4 was based on using CEM II with lower clinker share, scenario 5 was based on using CEM III everywhere. It can also be noted that scenario 6, the best in practice scenario still is higher than the average in Europe.

The scenario analysis also shows the extent of CO_2 emission reductions from different kind of abatement measures, where Figure 17 illustrates the resulting yearly emissions from cement used in the Swedish market for the different scenarios.

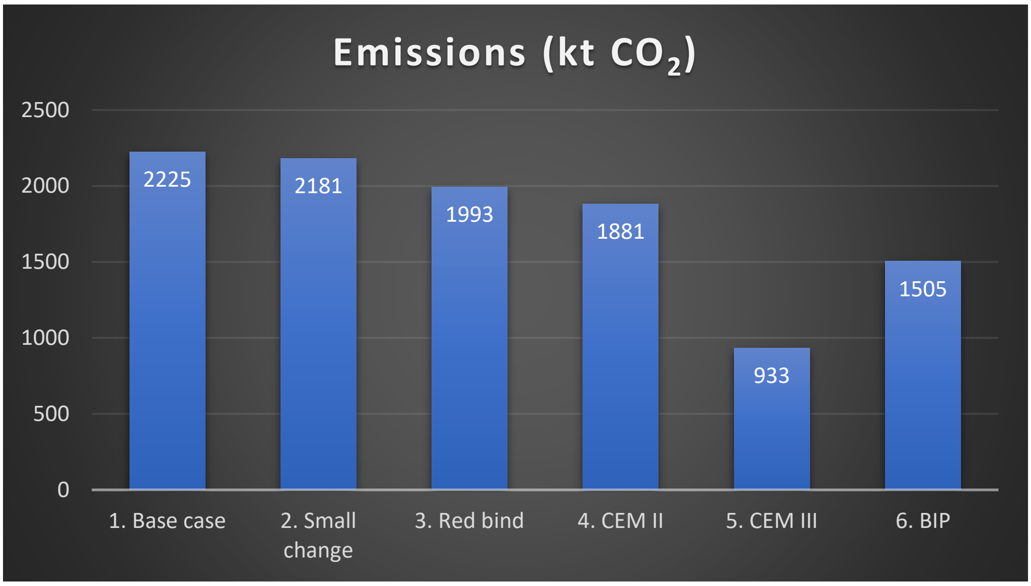


Figure 17 Annual resulting CO_2 emissions for cement production for the assessed scenarios.

As scenario 5 shows, the ideal abatement measure would be to be able to remove as much clinker as possible, but as stated in the scenario description this scenario is not seen a fully realistic in practice with today's SCMs. While Scenario 3 had the lowest material flow out of the scenarios, it is still far from the best scenario in terms of CO_2 emissions reduction. Scenario 6 on the other hand shows that a mix of the different solutions is one of the better solutions. This shows the importance of data gathering and working on several different solutions to achieve the best possible emission reduction.

7. Discussion

Measures to optimize the amount of cement used in concrete and to ensure that the right type of concrete is used in the right place could contribute to significantly reducing the overall climate impact from cement and concrete use. This work has been a first attempt to map the end use of cement in Sweden, implying a need to gather specific data, ranging from the type of cement that are produced by cement manufacturers, which exposure classes are used and where, to which type of cements are used in what type of construction projects to get a better picture of potential replacements. The cement ratio in the different exposure classes and uses would also be needed to analyze over-specification of cement compared to standards. As previously described however, there are a lot of data gaps in these areas and within the time limit of thesis it was only possible to scratch the surface.

The difficulty in data collection has several reasons:

- Lack of data – Existing statistical reports from industry associations providing an overview of concrete use in Europe is incomplete with inconsistent data from year to year, with evidence of several years between a complete set of data found for a single year in Sweden. Data may also be lacking since there previously has been no reason to keep detailed records [41].
- Difficulty to obtain specific data – With a single manufacturer of cement in Sweden, confidentiality and sensitivity of information is another issue. On the other hand, while the concrete and construction industry are intertwined, they are two different industries,

which instead poses challenges of obtaining enough quality data for the industry and the material uses to be accurately portrayed.

- Imported cement and concrete – Roughly 15% of the cement used is imported and concrete imports, particularly of precast elements are on the increase. This means that it is difficult to obtain direct data from cement or concrete manufacturers.

Filling the data gaps will be a challenge, and the data would be needed to be reported, quality assured and stored in a manner to be able to convert it into a statistical database useful for analysis purposes. Providing a better overview and more detailed data would require cooperation from most of the actors involved in the supply and use of cement and concrete.

A major challenge for the approximation model developed in this work was the description of the non-concrete based cement applications since no data was available describing annual production. Therefore, the estimates of mortar, screed and render applications are assumed to be used in the same quantities in terms of total percentage of cement material flow as in the UK. During this study, contact was made with SPEF (the Business Association for mortar and plaster construction) in the efforts of acquiring data. While there was no data available, SPEF expressed an interest in better knowledge about how much is produced among their members annually. Even if it is not the main share of cement use, it is still large enough to be relevant for calculating emissions from the cement sector. Because of the lack of data, it was also difficult to estimate what reductions could be done for this share, hence the scenario results for this category depends on the total cement production just as the base case scenario did.

Consequently, the results section of this study focused the binder intensity for the concrete based cement applications.

The approximation model is based on data describing domestically produced concrete, which means that cement which is imported in predominantly prefab concrete blocks is not accounted for in this approximation. No data on concrete imports is available in public and it is also unclear how much data that companies collect on imported products. As of today, there seems to be no obligation to report or keep statistics on these matters.

The importance of using SCMs are clear from the results of this study (cf. Figure 17). Even though scenario 3 which focuses on reducing the binder intensity has the lowest material flow (cf. Figure 15), it is still far behind the Best in Practice scenario (Scenario 6) in terms of CO_2 emission reduction. However, as discussed in the 2.1 SCM overview section, the problem with SCMs is the limited and diminishing supply. Sweden also faces another difficulty in this area since the domestic production of both fly ash and GGBFS is very low and projected to be even lower in the future. As can be seen in Figure 5, Sweden also seems to have a lack of suitable clays, although this image could be the result of lack of data since there seem to be available deposits in every other country except Finland. This could mean that if Sweden are going to keep producing the same type of cement it will most likely be dependent on importing SCMs or raw materials to such binders.

The scenario analysis gives an indication of the emissions reduction potential for abatement measures related to optimizing the amount of cement used in concrete. Scenario 6, current Best in Practice, would lower emissions by approximately 33% compared to today’s levels. However, these measures are far from being implemented on a large scale, and thus a lot of work remains if Sweden are to achieve net zero carbon emissions in 2045.

In addition to reducing the use of cement clinker, it will be important to reduce the CO_2 emissions from the primary production of cement. This would include efforts to switch fuel (or energy carrier) and/or invest in carbon capture and storage in the cement industry. As of today, Cementa is doing a research project together with electricity producer Vattenfall regarding electrification of the cement clinker process [40]. This would however bring the challenge of having enough green electricity produced, since many different industries are looking at electrification as a solution for fuel related emissions in their industry processes.

8. Conclusions

The main goal of this thesis is to construct an overview of the cement material flow in the Swedish society and mapping the end uses of cement. While there are many challenges associated with reducing CO_2 emissions within the cement and concrete industry, it is even more difficult to start if there is a lack of data describing the current situation. As it was not possible to create values and scenarios based on real data, this study gathered existing and similar data from recent studies and reports and developed an approximation model of cement material flow in society around this data. While gathering the limited available Swedish data, this study also looked abroad to see if similar studies had been made in other countries. The only comprehensive cement material flow study available was a study from the UK which means that even if more data is available in other countries, few have attempted to do a comprehensive study of a national cement material flow with detailed category splits [15].

This thesis has shown that there are several different ways depict a cement material flow and achievable emissions reductions, as the model created in this thesis was based on relatively gross data and yet managed to create an accurate representation of some major end-use categories. If the approach developed in this work can be complemented with more detailed data, it would also be possible to setup models with a more detailed perspective.

As mentioned, the supply of the most common SCMs today will be lower in the future, which means that other solutions need to be developed. However, currently available SCMs will still play an important role for the foreseeable future. It is important for the industry to both have a short term and long-term plan for emission reductions. Cementa seems to heavily rely on CCS to reduce the emissions in the long-term plan. While CCS is indeed likely to play an important role if to significantly reducing CO_2 emissions, it would be appropriate to consider alternative measures since there is yet to be any full-scale industrial CCS facilities in view of the limited incentives posed by the low prices of emissions rights within the EU emission trading scheme.

Cementa aims to be carbon neutral by 2030, but achieving this goal appears somewhat unlikely due to the reasons listed above. It would thus be advisable and complementary for the concrete and construction industry to also have a plan to reduce the material intensity as a means to achieve carbon emissions reductions.

Further, Cementa was previously denied expanding their limestone mining on Gotland, Sweden where the largest of their two factories are located. Although in early 2020 their expansion plans were approved, it was limited to 20 years and it contained clauses around possible ecosystem damage [21]. This would imply that the industry in the longer-term might not being able to produce the amount of concrete needed in society with the traditional materials used today. The demand for concrete could increase in line with a growing population and associated demand for new residences.

Sweden faces another challenge (cf. Table 3), as there are conservative rules which limits the reduction of material usage, levels of SCMs and use of SCMs other than fly ash and GGBFS. Further, while current binder intensity in Sweden is very high at 422 kg binder/m^3 concrete, there is no real reason that Sweden should not be able to achieve the same results as other countries in Europe with the average EU binder intensity being 317 kg/m^3 at current. Sweden also has a much higher clinker share then the average EU country with 86% compared to the European average of 73%. Consequently, as shown in this thesis, Sweden has a lot of improvement potential in various areas. Even greater potential for improvement is found when also taking account of design optimization towards reduced use of concrete, which has not been touched upon in this thesis.

The need for continued work is manifold, with one main topic being to get accurate data from the mortar, screed and render businesses to allow for a more detailed material flow. There is also a need to develop and make available more advanced statistics from the concrete industry, related to both end-uses, binder intensity and cement types used in various applications. This would be necessary to be able to analyze the usage (and potential over-usage) of cement and cement clinker in constructions and how to reduce both the cement use, the cement clinker use and the associated CO_2 emissions.

9. References:

[1] IPCC, “Special Report on Climate Change and Land,” 2019.

[2] UNFCCC, “Climate get the big picture understanding the UN climate change regime,” 2019. https://unfccc.int/resource/bigpicture/index.html#content-the-paris-agreemen (accessed Nov. 27, 2019).

[3] European Commission, “2020 Climate and Energy package,” *European Commission*, 2007. http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm (accessed Nov. 27, 2019).

[4] European Commission, “2030 Climate and Energy Framework,” *European Commission*, 2019. https://ec.europa.eu/clima/policies/strategies/2030_en (accessed Nov. 27, 2019).

[5] European Commission, “Factsheet: Long-term strategy for GHG emissions reductions,” 2018. [Online]. Available: https://ec.europa.eu/clima/sites/clima/files/docs/pages/vision_1_emissions_en.pdf.

[6] Energimyndigheten, “Sveriges energi- och klimatmål.” https://www.energimyndigheten.se/klimat--miljo/sveriges-energi--och-klimatmal/ (accessed Dec. 11, 2019).

[7] J. Timperley, “Q&A: Why cement emissions matter for climate change,” 2019. https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change (accessed May 01, 2019).

[8] A. Favier, K. Scrivener, C. De Wolf, and G. Habert, “A sustainable future European cement and concrete industry,” 2018.

[9] J. Lehne and F. Preston, “Chatham House Report Making Concrete Change Innovation in Low-carbon Cement and Concrete #ConcreteChange,” *Chatham House Rep.*, pp. 1–122, 2018, doi: 10.1088/1742-6596/1015/3/032163.

[10] ETC, “Mission Possible Report Summary,” 2018.

[11] M. Erlandsson, T. Malmqvist, N. Francart, and J. Kellner, “Minskad klimatpåverkan från nybyggda flerbostadshus - Underlagsrapport,” 2018.

[12] Understanding Cement, “Cement History,” 2019. https://www.understanding-cement.com/history.html (accessed Aug. 22, 2019).

[13] R. M. Andrew, “Global CO_2 emissions from cement production,” *Earth Syst. Sci. Data*, 2018, doi: 10.5194/essd-10-195-2018.

[14] International Energy Agency, “Technology Roadmap: Low-Carbon Transition in the Cement Industry,” 2018.

[15] W. Shanks, C. F. Dunant, M. P. Drewniok, R. C. Lupton, A. Serrenho, and J. M. Allwood, “How much cement can we do without? Lessons from cement material flows in the UK,” *Resour. Conserv. Recycl.*, vol. 141, no. October 2018, pp. 441–454, 2019, doi: 10.1016/j.resconrec.2018.11.002.

[16] R. Snellings, G. Mertens, and J. Elsen, “Supplementary cementitious materials,” *Reviews in Mineralogy and Geochemistry*. 2012, doi: 10.2138/rmg.2012.74.6.

[17] S. E. Carmona, “Concrete Change: Exploring the effects of scaling up the use of alternative binders to reduce the climate impact from concrete,” Chalmers University of Technology, 2019.

[18] J. Rootzén and F. Johnsson, “Managing the costs of CO2 abatement in the cement industry,” *Clim. Policy*, pp. 1–20, 2016, doi: http://dx.doi.org/10.1080/14693062.2016.1191007.

[19] J. L. Fan, M. Xu, L. Yang, X. Zhang, and F. Li, “How can carbon capture utilization and storage be incentivized in China? A perspective based on the 45Q tax credit provisions,” *Energy Policy*, vol. 132, no. July, pp. 1229–1240, 2019, doi: 10.1016/j.enpol.2019.07.010.

[20] Naturskyddsföreningen Gotland, “Cementa AB ansökan om tillstånd till fortsatt och utökad täktverksamhet samt vattenverksamhet vid Slite , Gotlands kommun Yttrande över ansökan,” 2018.

[21] Sveriges Domstolar, “Mark- och miljödomstolen lämnar tillstånd till fortsatt kalkbrytning i Slite på Gotland,” 2020. https://www.domstol.se/nyheter/2020/01/mark--och-miljodomstolen-lamnar-tillstand-till-fortsatt-kalkbrytning-i-slite-pa-gotland/.
[22] A. Favier, C. De Wolf, K. Scrivener, and G. Habert, “A sustainable future for the European cement and concrete industry: Technology assessment for full decarbonisation of the industry by 2050,” p. 96, 2018, doi: 10.3929/ethz-b-000301843.
[23] J. (Golvbranschen G. Adnerfall, “Modern tät betong,” *Bygg & Teknik*, Aug. 2018.
[24] Bygg- och anläggningssektorn, “Färdplan för fossilfri konkurrenskraft Bygg- och Anläggningssektorn,” p. 28, 2018, [Online]. Available: http://fossilfritt-sverige.se/verksamhet/fardplaner-for-fossilfri-konkurrenskraft/.
[25] Svensk Betong, “Betongindikatorn.” https://www.svenskbetong.se/svensk-betong/branschen/betongindikatorn (accessed Jun. 20, 2019).
[26] M. D. A. Thomas, “Optimizing the Use of Fly Ash in Concrete,” *Portl. Cem. Assoc.*, 2007.
[27] D. Suresh and K. Nagaraju, “Ground Granulated Blast Slag (GGBS) In Concrete – A Review,” *J. Mech. Civ. Eng.*, vol. 12, no. 4, pp. 76–82, 2015, doi: 10.9790/1684-12467682.
[28] Swedish Standards Institute, “Svensk standard SS-EN 197-1:2011,” 2013.
[29] E. Smrčková, M. Bačuvčík, and I. Janotka, “Basic characteristics of green cements of CEM V/A and V/B kind,” in *Advanced Materials Research*, 2014, doi: 10.4028/www.scientific.net/AMR.897.196.
[30] Portland Cement Association, “Ready Mixed Concrete Congress,” *Concrete*. https://www.cement.org/cement-concrete-applications/products/ready-mixed-concrete (accessed May 22, 2019).
[31] K. Elliott, “What is precast concrete?,” *Precast Concrete Structures*, 2019. .
[32] Swedish Standards Institute, “Svensk standard SS-EN 206:2013+A1:2016,” 2018.
[33] Svensk Betong, “Betongkvalite och exponeringsklass,” 2019. https://www.svenskbetong.se/bygga-med-betong/bygga-med-platsgjutet/statik/kontorshus/vaggar-och-pelare/val-av-betongkvalitet-och-exponeringsklass (accessed Dec. 11, 2019).
[34] E. Kurkinen, J. Norén, D. Peñaloza, N. Al-Ayish, and O. During, “Energi och klimateffektiva byggsystem: Miljövärdering av olika stomalternativ,” 2017.
[35] C. Müller, “Use of cement in concrete according to European standard EN 206-1,” *HBRC J.*, 2012, doi: 10.1016/j.hbrcj.2012.08.001.
[36] Boverket, “Klimatdeklaration av byggnader,” 2018.
[37] Swedish Government, “Klimatdeklaration vid uppförande av byggnader,” 2019. https://www.regeringen.se/pressmeddelanden/2019/09/klimatdeklaration-vid-uppforande-av-byggnader/ (accessed Dec. 13, 2019).
[38] Trafikverket, “Resultatkonferens Klimatkrav och Klimatkalkyl 2018,” 2018.
[39] Svensk Betong, “Klimatförbättrad betong,” 2019, [Online]. Available: https://www.svenskbetong.se/images/pdf/klimatforbattrad_betong_webb3.pdf.
[40] Cementa, “Färdplan cement för ett klimatneutralt betongbyggande,” 2018. [Online]. Available: http://fossilfritt-sverige.se/verksamhet/fardplaner-for-fossilfri-konkurrenskraft/.
[41] ERMCO, “STATISTICS 2003 – 2017,” 2019. http://ermco.eu/new/statistics-2003-2016/ (accessed Dec. 10, 2019).
[42] Energimyndigheten, “Industrins processrelaterade utsläpp av växthusgaser och hur de kan minskas ER 2018:24,” 2018.
[43] P. L. Daniels and S. Moore, “Approaches for quantifying the metabolism of physical economies: Part I: Methodological overview,” *J. Ind. Ecol.*, 2001, doi: 10.1162/10881980160084042.
[44] N. Olsson, “Private Communications with NCC,” 2019.
[45] M. Amer, T. U. Daim, and A. Jetter, “A review of scenario planning,” *Futures*, 2013, doi: 10.1016/j.futures.2012.10.003.
[46] Cementa, “Miljödata Cementa.”

https://www.cementa.se/sv/search?keywords=miljödata (accessed Dec. 13, 2019).

[47] Naturvårdsverket, “Klimatscenarier för bygg - och fastighetssektorn - Förslag på metod för bättre beslutsunderlag,” 2019.