Lund University

Department of Technology and Society
Environmental and Energy Systems Studies

Life Cycle Assessment of Concrete

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Master thesis

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Livscykelanalys av betong

Sammandrag

Detta är en studie på betong som följer metodiken för en livscykelanalys (LCA). Studien är gjord för två typer av betong, vanlig husbyggnadsbetong och frostbeständig betong som används vid brobygge. Speciellt fokus läggs på det flyttillsatsmedel som tillsätts i betongen. Användningsfasen är inte medtagen i studien på grund av att det inte är specificerat vilken typ av betongkonstruktion som betongen används i och betongen antas även vara inert under denna fas.

Resultaten visar att det är råmaterialproduktionen och transporterna som är de största bidragande orsakerna till betongens totala miljöpåverkan. Den process i råmaterialproduktionen som bidrar mest till miljöpåverkan är cementproduktionen. Inom transporterna så är det transporten av betong, följt av transporten av cement till depå som bidrar mest. Miljöpåverkan från frostbeständig betong är mellan 24-41 % högre än den från normal betong. Orsaken till detta är att den frostbeständiga betongen innehåller mer cement. Flyttillsatsmedel bidrar med mellan 0.4-10.4 % av betongens totala miljöpåverkan, minst till växthuspotentialen (GWP) och mest till potentialen för bildningen av fotokemiska oxidanter (POCP). Även toxiciteten hos flyttillsatsmedeln har bedömts och slutsatsen är att det låga läckage av flyttillsatsmedel som sker från betong sannolikt inte orsakar någon risk för varken miljö eller människor.

Nyckelord

Livscykelanalys, LCA, betong, flyttillsatsmedel

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Abstract

This is an environmental study on concrete that follows the standard protocol of life cycle assessment (LCA). The study is done for two types of concrete, ordinary and frost-resistant concrete, and has an extra focus on the superplasticizers used as admixtures. The utilization phase is not included in this study since the type of construction for which the concrete is used is not defined and the concrete is assumed to be inert during this phase.

The results show that it is the production of the raw material and the transports involved in the life cycle of concrete that are the main contributors to the total environmental load. The one single step in the raw material production that has the highest impact is the production of cement. Within the transportation operations the transportation of concrete is the largest contributor, followed by the transportation of the cement. The environmental impact of frost-resistant concrete is between 24-41 % higher than that of ordinary concrete due to its higher content of cement. Superplasticizers contribute with approximately 0.4-10.4 % of the total environmental impact of concrete, the least to the global warming potential (GWP) and the most to the photochemical ozone creation potential (POCP). Also the toxicity of the superplasticizers is investigated and the conclusion is that the low amount of leakage of superplasticizers from concrete leads to a low risk for the environment and for humans.

Keywords

life cycle assessment, LCA, concrete, superplasticizer

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PREFACE

This Master thesis finishes my degree in Environmental Engineering at Lund Institute of Technology, Lund University. The project is done at Environmental and Energy systems studies, within the research programme Greenchem.

I would like to thank my supervisor associate professor Pål Börjesson and also Linda Gustafsson at Environmental and Energy systems studies for all their help and engagement in my project. I would also like to thank those who have helped me with data for my calculations.

Malmö, 2005-09-19

Jeannette Sjunnesson

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1 INTRODUCTION

1.1 Background

This Master thesis is done within the research programme Speciality Chemicals from Renewable Resources, Greenchem, at Lund University. This programme, which is a co-operation between the university and several companies, has its focus on developing chemicals and materials with low environmental impact in a production with low environmental impact, and based on renewable raw materials. The research focuses on three different product groups: biosurfactants (e.g. pharmaceuticals, hygiene products and concrete), wax esters (e.g. coatings, cosmetics and pharmaceuticals) and epoxides (e.g. coatings, lubricants, paints and start material for a number of different products). This study comes under the heading biosurfactants, as a preliminary study to evaluate the present environmental impact of concrete and superplasticizers. The results are to be used as a reference in the evaluation of new superplasticizing agents from an environmental point-of-view. Today superplasticizers are made from crude oil, which is a raw material of fossil origin. To replace the fossil-based surfactants the Greenchem programme is developing new production methods based on enzymatic syntheses and renewable resources.

1.2 Aims and objectives

The aim of this study is to analyse concrete from an environmental point-of-view, using a life cycle approach. The objective is to show which phases in the life cycle of concrete have a high impact and why. The phases included are raw material production, concrete production, transport operations and demolition.
The study does not specify the type of construction that the concrete is used in, which is the reason why the utilization phase is excluded. It is assumed that concrete is inert during this phase.

One question to which special attention will be given is: What is the contributing part from superplasticizers to the total environmental impact of concrete? To fulfil the aims of this study, each step in the concrete life cycle will be presented so that the data can be used separately or together in further analyses in different situations.

2 CONCRETE – A GENERAL DESCRIPTION

Approximately 3.7 million tons of concrete were used in Sweden in buildings, roads and other constructions in 2004.[1] This makes concrete one of the most common building materials on the market. The main ingredients in concrete are aggregate (70-80 %), cement (10-20 %) and water (7-9 %), and to enhance specific characteristics, chemical admixtures (less than 1 %) are added.[2]

2.1 Raw material

2.1.1 Cement

Cement is a hydraulic binder, which hardens when it is mixed with water.[3] The main constituents of cement are limestone and clay. To produce cement (see ***Figure 1***) the limestone and clay are ground together. This raw material, called raw meal, is fed into a rotating kiln either wet or dry. Dry material is more often used since this is more energy efficient, as a wet kiln uses twice as much energy. The temperature in the kiln is approximately 1450 °C.[4]

The calcination process begins when the material passes from the kiln to the calcinator. In this heating process CO_2 is released from the limestone to produce cement clinker. The clinker consists of a mineral residue containing calcium oxide (CaO), alone or together with iron (Fe), aluminium (Al) or silicon (Si). The chemical process is: $CaCO_3$ + heat ➔CaO + CO_2. Most of the energy used in cement production is used in the calcination process.[5]

The last step in cement production is the grinding together of the cement clinker and gypsum.[6] Gypsum is added to prolong the binding of cement. Other material may be added the cement, for example, bauxite or sand, to establish the required quality of the final product. After finishing and packaging, the cement is transported to cement depots.[7]

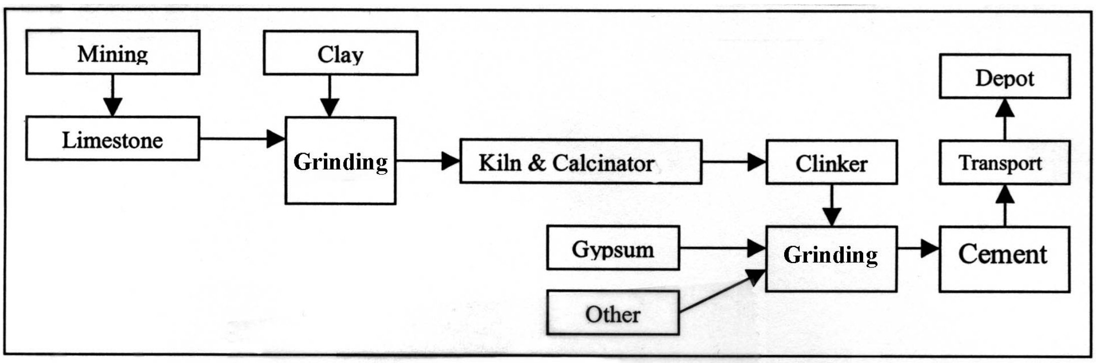

Figure 1 Flowchart of cement production

[1] Statistiska centralbyrån, 2005
[2] Fagerlund, 1999
[3] Johansson, 1994
[4] Burström, 2001
[5] ibid
[6] Johansson, 1994
[7] ibid

The word “cement” refers in most cases to Portland cement, since 95 % of all cement produced is of this type. Portland cement is characterized by the way it is produced and by its composition, i.e. the production presented here and the composition of calcium, silica, aluminium and iron. The name is not a trademark but a type of cement, just like sterling is a type of silver.[8]

According to the Swedish Standard, SS 13 42 01 based on European pre-standard ENV 197-1, cement is divided into three groups called CEM I, CEM II and CEM III. These types indicate how much Portland cement is included in the cement. CEM I has approximately 95-100 % of Portland cement, CEM II has at least 65 % and CEM III has between 20-65 % of Portland cement. Other ingredients in cement can be, for example, blast furnace slag, fly ash or puzzolanic material.[9] The compositions vary for different fields of application.

2.1.2 Aggregate

Aggregate is either macadam or gravel. Gravel is natural stone and macadam is crushed rock. Because of their different origin they have a different texture, see ***Figure 2***a. To optimize its function aggregate of all sizes should be included in the concrete. The smaller fractions will fill cavities between bigger fractions and the concrete paste will fill the smallest cavities and act like glue between the aggregate[10], see ***Figure 2***b.

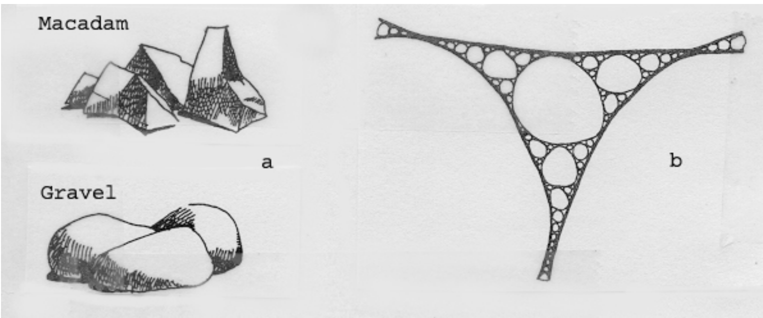

Figure 2 a) Characterization of aggregate and b) the ideal aggregate that fills a cavity to the maximum.[11]

The crushed stone material in production of macadam is passed through a sieve to remove the small particles. Since macadam consists of rough-edged particles, it is more stable as filling material because of its ability to lock. Gravel is extracted from a gravel pit and has a naturally rounded shape.[12] Macadam is used to a greater extent since natural gravel is a more limited resource. The proportion of natural gravel to macadam also depends on the location, i.e. whether good supply of gravel is available.

[8] Portland cement, [2005-06-09]
[9] Burström, 2001
[10] ibid
[11] Burström, 2001 pages 211-212
[12] Sydsten – *Makadam*, [2005-04-27]

2.1.3 Admixtures

There are two types of admixtures, chemical and mineral. Mineral admixtures are, for example, fly ash and silica powder, which are not analysed in this study. Chemical admixtures included in the analysis are air-entraining admixtures and superplasticizers.

Air-entraining admixtures create numerous small air bubbles (approximately 0.05-0.3 mm) in the concrete. These bubbles function as an extra space for expanding interstitial water when the temperature drops below freezing point and prevents the concrete from cracking. The air trapped in the bubbles will not evaporate since the concrete paste is practically impermeable. In unhardened concrete the admixture prevents water separation and increases the workability.[13] Air-entraining admixtures are made from organic material.[14]

Superplasticizers, also called high-range, water-reducing admixtures, are used because of their ability to drastically reduce the amount of water in concrete and still keep the same consistency of un-hardened concrete. Less water in the concrete leads to a lower ratio between water and cement and thereby higher strength, lower permeability and higher durability.[15] Normal plasticizers, also called water-reducing admixtures, can reduce the water content up to 8-10 %. Superplasticizers can reduce the water content up to 30 %.[16]

Superplasticizers are more common than air entraining admixtures in concrete, and represent approximately 38 %, while normal plasticizers are approximately 40 % of all admixtures sold in Europe (2002).[17]

Superplasticizers can be based on sulphonated melamine formaldehydes (SMF), sulphonated naphthalene formaldehydes (SNF), vinyl copolymers and poly-carboxylic ethers.[18] The superplasticizer used in the recipes in this paper is called Peramin F and is based on sulphonated melamine formaldehydes.[19] This is produced by various chemical reactions between the starting materials melamine, formaldehyde and sodium bisulphite. The molecular structure of SMF is shown in ***Figure 3***.[20]

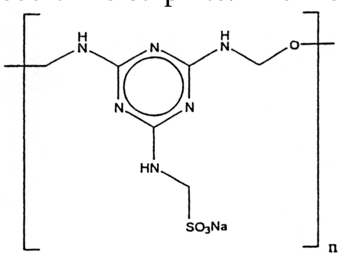

Figure 3 The molecular structure of Sulphonated Melamine Formaldehyde, SMF[21]

[13] Burström, 2001
[14] Ramachandran et al., 1998
[15] Burström, 2001
[16] Ramachandran et al., 1998
[17] EFCA Environmental Declaration Superplasticizing Admixtures, 2002
[18] ibid
[19] Safety Data Sheet, Peramin F, Perstorp Speciality Chemicals AB
[20] Ramachandran et al., 1998
[21] Ramachandran et al., 1998 page 46

2.2 Concrete production

Mixing the aggregate and admixtures together with concrete paste makes concrete. The admixture can be added differently, for example, before transport or before casting or already during cement production, depending on what kind of effect is to be achieved.[22]

The concrete paste is cement mixed with water and it is the binder in the concrete. Its characteristics are controlled by the ratio of water to cement, the w/c ratio. If the concrete is mixed and worked up appropriately the strength of the concrete is determined by the w/c ratio.[23]

$w/c = \frac{weight\ of\ water}{weight\ of\ cement}$, where the weights are in [kg] or [kg/m^3].

2.3 Concrete hardening

The development of concrete during hardening can be divided into four phases. The first phase is green concrete, the second phase is young concrete, the third phase is the hardening phase, i.e. when the strength grow, and the forth phase is the hardened concrete (***Figure 4***).[24]

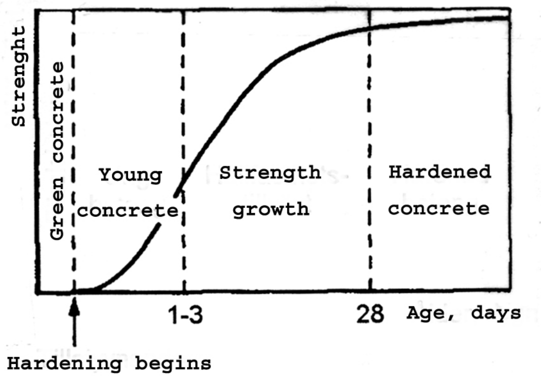

Figure 4 The development of concrete during hardening.[25]

The most important characteristics of green concrete are workability and stability.[26] The workability is connected to the concrete deformation characteristics and depends on the concrete paste and aggregate. Factors that influence the workability are:[27]

- amount of water (i.e. w/c ratio)
- amount of cement (i.e. w/c ratio)
- aggregate grading
- amount of fine aggregate and particle shape
- admixtures, both chemical and mineral

A stable concrete will remain homogeneous during the whole concrete cycle, i.e. from green to hardened concrete. If the concrete is inhomogeneous a separation may occur.

[22] Fagerlund, 1999
[23] Burström, 2001
[24] ibid
[25] Burström, 2001 page 224 (translated)
[26] Burström, 2001
[27] Johansson & Petersons, 1994

There are three kinds of separation: water separation, stone separation and mortar separation (***Figure 5***).[28]

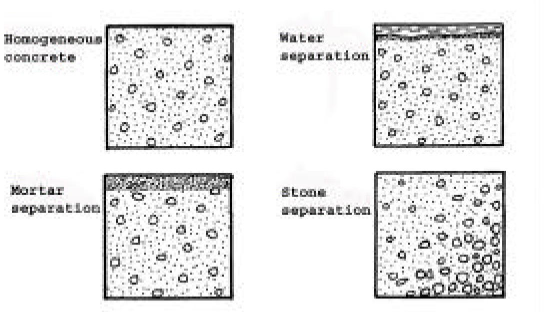

Figure 5 Homogeneous concrete compared to different kinds of separation[29]

Water separation arises when there is too little fine aggregate in the concrete so the concrete cannot retain all the water. The water separates from the concrete paste and accumulates on the concrete surface. Water separation is affected by the cement characteristics and the w/c ratio.[30]

Stone separation means that larger aggregates sink to the bottom leading to a differentiation of the strength of the concrete in different parts of the mass. Stone separation is affected by the need of vibration and transportation time.[31] The risk of separation can be decreased by optimized use of aggregate (see section 2.1.2).[32]

Mortar separation can occur when the concrete is too loose. In mortar separation the concrete separates into two layers, one above the other, with different characteristics, i.e. in principle producing two different kinds of material.[33]

Young concrete is defined as having an age of less than 28 days. In this state the concrete is very sensitive to dehydration, temperature fluctuation and weight because of the rapid changes these cause in the characteristics of the concrete.[34] For this reason the concrete must be kept moist for the first few days after pouring.

When the concrete is mixed a reaction begins between the cement and the water, hydration, which continues from the green state till the hardened state. Hydration is an exothermic reaction in which CaO-containing minerals react with water to form $Ca(OH)_2$ with the release of heat. This heat is produced mainly within the first 24 hours after concreting and then declines. Approximately 230 kJ of heat per kg cement has been released after the first day. The total release is approximately 325 kJ per kg cement. The amount of heat released depends on the kind of cement being used.[35]

[28] ibid
[29] Burström, 2001 page 222, (translated)
[30] Johansson & Petersons, 1994
[31] Burström, 2001
[32] Johansson & Petersons, 1994
[33] Burström, 2001
[34] Ljungkrantz et al., 1994
[35] Burström, 2001

During the hardening phase the mechanical characteristics are still developing but the concrete will no longer be influenced by any major external changes. The most significant characteristic of hardened concrete is its compressive strength. Closely related to the compressive strength are durability and density. The most common factors in Sweden that might cause reduced durability are:[36]

- frost attacks
- corrosion in the reinforcement bars
- chemical attacks

These factors can be minimized by using the quality of concrete most appropriate to the prevailing conditions.

2.4 Types and qualities

There are several different types of concrete just as there are many fields of application. They are, for example, normal concrete, high-strength concrete, high-performance concrete, self-compacting concrete, light-weight concrete, frost-resistant concrete and light-weight aggregate concrete. The production processes of the different kinds of concrete are similar. In this study two types of concrete are analysed, namely, ordinary concrete for house construction (C20/25) and frost-resistant concrete for bridge construction (C35/45).

The quality of concrete is defined by its compressive strength since this gives an over-all picture of the quality.[37] The compressive strength is measured using a test cylinder (cylinder strength) and a test cube (cubic strength) of hardened concrete. The values of the strength are given by the name, for example C20/25 means that the cylinder strength is 20 MPa and the cubic strength 25 MPa. The cylinder is 150 mm in diameter and has a height of 300 mm, while the cube has a side of 150 mm. The test cylinder and test cube are stored for 28 days under water before the test, according to Swedish Standard (SS-EN 206-1).[38]

2.5 Water quality

It is important to have good water quality since this will affect quality and strength of the concrete. A common rule is that drinking water is of sufficiently high quality to be used as mixing water. In some cases water of lower quality can be used. Cleaning water, for instance, is often reused as mixing water.[39]

2.6 Concreting

There are different ways of concreting, *in situ* concreting or precast concreting. In *in situ* concreting the concrete is mixed at the factory and then delivered as green concrete to the construction site where it is cast. This concrete is called ready-mixed concrete. Alternatively the concrete is mixed in the factory and cast into concrete element there, and are then transported to the construction site. The results of the two types are practically the same and the different methods have both pros and cons.[40]

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[36] ibid
[37] ibid
[38] Lyhagen, 2005
[39] Klingstedt, 1994
[40] Fagerlund, 1999

In *in situ* concreting the concrete is mixed and poured into a rotating concrete vessel, which makes the concrete more homogenous and therefore more workable. At the construction site the concrete is pumped out into a mould and is then compressed by vibration. The vibration makes the concrete fill all cavities in the mould. Self-compacting concrete does not need any or very little vibration. The hardening process of the concrete begins when the concrete is mixed and the cement and water react. To maintain a continuous hardening the concrete must be kept moist for a few days. When mixed, concrete is pliable for only a few hours before it begins to harden.[41] When using *in situ* concreting, a mould as well as reinforcement has to be built at the construction site. This method is dependent on weather conditions but the use of a concrete of higher quality can reduce this impact. One can also prevent unwanted weather-related effects by adding chemical admixtures. An *in situ*-built construction has normally better noise insulation since it can be made seamless. It is also more durable and stable than a construction of concrete elements.

In precast concreting the concrete elements are made differently depending on their function, a house wall, a façade, a balcony or a concrete beam. The concreting is the same as for *in situ* concreting but the cast is done indoors and with more permanent equipment. The use of concrete elements enhances the efficiency of the construction place. The concrete elements must be “glued” together accurately with the right kind of glue and this stage necessarily depends on the weather conditions. When a construction is demolished, precast concrete elements are easier to break down.[42] The best way to construct is often to combine the two methods, for example, by an *in situ* cast frame and a façade of precast elements. Concrete elements are easier to make aesthetically pleasing than *in situ* cast concrete.[43]

2.7 Carbonization

Carbonization is the process of CO_2 diffusing into the concrete and reacting with calcium dihydroxide, $Ca(OH)_2$, turning the concrete back to $CaCO_3$ (*Reaction formula:* $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$).[44]

The carbonization rate depends on CO_2-concentration and humidity in the ambient air. Since carbonization is gas diffusion the process is slower with increasing humidity. It also depends on the density of the concrete, i.e. the w/c ratio[45] and whether there are any surface coatings, for example, paint or wallpaper that reduce the CO_2-diffusion into the concrete. Carbonization is an unwanted effect in construction since it “opens up” the concrete barrier to penetration of unwanted compounds and it also lowers the pH-value in the concrete. This can lead to increased initiation of corrosion and chemical attacks in the concrete.[46] Full carbonization takes a very long time and it can take centuries before the carbonization of a concrete construction or demolished concrete is complete.

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[41] ibid
[42] ibid
[43] ibid
[44] Burström, 2001
[45] Fagerlund, 1992
[46] Burström, 2001

2.8 Demolition

When concrete constructions are demolished, the concrete is normally reusable. Concrete is transported to a recycling station, where the reinforcement bars are removed and the concrete is crushed into suitable size depending on its future. It can, for example, be used as filling material in road construction or as new aggregate material in concrete production. Larger pieces of concrete elements can be used as embankment material instead of being crushed. Reusing concrete leads to a reduced use of virgin natural resources such as stone and gravel.[47]

[47] Sysav, [2005-05-11]

3 ENVIRONMENTAL ASSESSMENT

This environmental assessment follows the standard protocol of life cycle assessments, LCA, (ISO 14040-14043). LCA is a method used to evaluate the environmental impact from the entire life cycle of a product, from "the cradle to the grave". Here life cycle inventory (LCI) data were collected from existing LCA reports, environmental reports and communication with key actors on the concrete and cement market. The results are presented both per kg material for each raw material and per functional unit (FU) (see APPENDIX C – Inventory tables) which is equivalent to 1 m^3 of concrete.

In this study, which describes the environmental impact of two different types of concrete, a FU of 1 m^3 can be used. But in future analysis a FU of, for example, 1 km bridge or 1 m of pipe can be used. Another possibility is to include a time dimension, for example, 1 km bridge during 100 years. When comparing the environmental impact of the concrete life cycle containing different kinds of superplasticizers a FU that consider both function and time might give a better result than the change in 1 m^3 that is chosen in this study.

3.1 System boundaries

The phases of the life cycle of concrete included in this study are shown in ***Figure 6***. The casting is excluded because of difficulties in gathering data, since the energy demand differs depending on the kind of concrete construction to be made. An estimation is, however, that the energy input and emissions from this phase are limited. The use of water as a raw material is also excluded since water is not regarded as a limited resource.

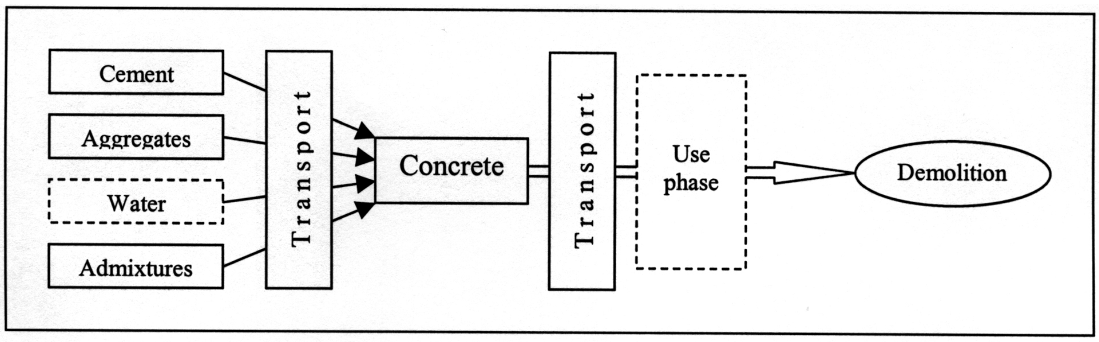

Figure 6 General flowchart for the concrete life cycle

The production of concrete studied here is located in Sweden and so are the production/extraction of raw material and the demolition of used concrete. The impact from the manufacture of machines and other equipment used in the different processes is not included in the study. Further use of demolition products, for instance, filling material and concrete aggregate, are not included within the limits of the system.

To get a fair picture of the environmental impact of concrete, the time-frame must be sufficiently long. However, the carbonization of concrete will not be taken into consideration since the duration of this process is too long for this study (see section 2.7).

3.2 Data

Data for the production of cement at a factory is specific for Cementa AB[48]. These factories have highly developed technologies and the data were collected in 2002. Data for macadam production are collected via personal communication with Sydsten AB[49] and refer to average data for recent years. Data for gravel production are taken from an existing LCA report[50]. Data for superplasticizers were taken from an EPD by the European Federation of Concrete Admixture Associations (EFCA)[51] from 2000-2001. Data for concrete production are taken from environmental reports from two factories in the group of Sydsten AB[52] and refer to average data from one small (Sjöbo) and one large factory (Malmö). Demolition data are collected by personal communication with a subcontractor to Ågab Syd/Sysav.[53] Transportation data are taken from NTM.[54]

The proportions of the components in the two types of concrete used in this study are presented in ***Table 1*** and ***Table 2***. The compression strength of the ordinary concrete is 31.2 MPa, w/c=0.65 and the density is 2330 kg/m^3. For the frost-resistant concrete the corresponding values are 53.2 MPa in compression strength, w/c=0.40 and density 2370 kg/m^3.[55] The overall density of concrete is 2400 kg/m^3 and this value is used in this study. Complete LCI data and calculations are presented in APPENDIX A – LCI data.

Table 1 Proportions for ordinary concrete[56]

Ordinary concrete for house construction		
C20/25 16 S4		
	kg/m^3	%
Cement	295	13
Macadam	749	32
Natural gravel	1093	47
Superplasticizer (Peramin F)	1.51	0.06
Total amount of water	202	8.6

[48] Cementa och Miljön – Verksamhetsåret 2002, 2002
[49] Linné, March 2005
[50] Stripple, 2001
[51] EFCA Environmental Declaration Superplasticizing Admixtures, 2002
[52] Weywadt, March 2005
[53] Palm, March 2005
[54] NTM, Nätverket för Transporter och Miljön, [2005-05-13]
[55] Lyhagen, March 2005
[56] ibid

Table 2 Proportions for frost-resistant concrete[57]

Frost-resistant concrete for bridge construction C35/45-25-S2-Lu Anl Frost VCT 0,40		
	kg/m^3	%
Cement	434	18
Macadam	951	40
Natural gravel	828	35
Superplasticizer (Peramin F)	0.95	0.04
Air-entraining admixture (Peramin HPA)	3.3	0.1
Total amount of water	167	7

Inventory results for the superplasticizer, Peramin F, are valid for four main groups of superplasticizers: sulphonated naphthalene formaldehyde, sulphonated melamine formaldehyde, vinyl copolymers and poly-carboxylic ethers.[58] The air-entraining admixture, Peramin HPA, used in the recipes contains sulphonates and alkyl alcohols.[59] Since LCI data were not available for the air-entraining admixture the data for superplasticizers are used instead.

3.3 Allocations

Allocation has been made for macadam production. Other allocations are already included in the LCI data collected from the literature used.

3.4 Environmental impact categories

The impact assessment categories included are energy use, Global Warming Potential (GWP), Eutrophication Potential (EP), Acidification Potential (AP), Photochemical Oxidant Creation Potential (POCP) and toxicity of superplasticizers.

3.5 Data quality

Data for raw material production, concrete production and transports are taken from 2000 and later, which is an accepted time span for this type of study. The studies used in the evaluation of the toxicity of superplasticizers are done in 2004.

Since the data are taken from no earlier than year 2000 the processes used in the production of raw material and concrete are based on recent technologies and normal production conditions.

[57] ibid
[58] EFCA Environmental Declaration Superplasticizing Admixtures, 2002
[59] Safety Data Sheet, Peramin HPA, Perstorp Speciality Chemicals AB

4 INVENTORY RESULTS

4.1 Cement

Inventory results for cement production are given in ***Table 3***. In the cement factory alternative fuels such as car tyres and bone meal are used. The car tyres have higher energy content than coal while bone meal has approximately the same as coal. For calculations see APPENDIX A – LCI data.

Table 3 Energy demand and emissions generated in the production of 1 kg cement

Energy	
Coal	1.9 MJ
Coke	0.51 MJ
Diesel	0.03 MJ
Car tyres	0.42 MJ
Bone meal	0.01 MJ
Electricity	0.48 MJ
Emissions to air	
CO_2	0.71 kg
CO	2.7 mg
NO_x	0.7 g
SO_x	0.09 g
CH_4	2.6 g
HC	1.3 mg

4.2 Aggregates

In macadam production diesel is used in internal transports. All of the crushing machines are driven by electricity. In the extraction of gravel a wheel loader is used to excavate the gravel, while the internal transports use lorry loaders.[60] Inventory results for macadam and gravel production are given in ***Table 4*** and ***Table 5***. For calculations see APPENDIX A – LCI data.

Table 4 Energy demand and emissions generated in production of 1 kg macadam

Energy	
Diesel	0.02 MJ
Electricity	0.03 MJ
Emissions to air	
CO_2	1.6g
CO	0.81 mg
NO_x	14mg
SO_x	0.78mg
CH_4	1.7mg
HC	0.9mg

[60] Stripple, 2001

Table 5 Energy demand and emissions generated in the production of 1 kg gravel

Energy	
Coal	9.6E-05MJ
Oil	1.0E-03MJ
Peat	1.1E-05MJ
Natural gas	2.2E-05MJ
Biomass fuel	1.1E-04MJ
Electricity	2.4E-03MJ
Emissions to air	
CO_2	0.07g
CO	0.07mg
NO_x	0.6mg
SO_x	0.05mg
CH_4	0.38µg
HC	0.04mg

4.3 Admixtures

Inventory results for the superplasticizer are presented in ***Table 6***.[61]

Table 6 Energy demand and emissions for the production of 1 kg superplasticizer

Energy	
Coal	1.7MJ
Crude oil	3.2MJ
Natural gas	8.2MJ
Electricity	2.9MJ
Emissions to air	
CO_2	0.69kg
CO	2.1g
NO_x	3.5g
SO_x	6.6g
CH_4	1.2g
HC	2.2g

4.4 Concrete production

The inventory results for concrete production (mixing) are shown in ***Table 7***. For calculations see APPENDIX A – LCI data.

Table 7 Energy demand and emissions to air for the production of 1 m^3 of concrete

Energy	
Oil	15MJ
Electricity	33MJ
Emissions to air	
CO_2	1.5kg
CO	0.86g
NO_x	2.3g
SO_x	3.3g
CH_4	1.7g
HC	0.32g

[61] EFCA Environmental Declaration Superplasticizing Admixtures, 2002

4.5 Demolition

The energy needed for demolition is estimated to vary between 0.006-0.008 MJ/kg concrete, with an average of 0.007 MJ/kg (***Table 8***). For calculations see APPENDIX A – LCI data.

Table 8 Energy demand and emissions to air for the demolition of 1 kg of concrete

Energy		
Diesel	0.007	MJ
Emissions to air		
CO_2	0.54	g
CO	0.09	mg
NO_x	5.3	mg
SO_x	0.28	mg
CH_4	0.01	mg
HC	0.31	mg

4.6 Transports

The transports for the raw materials and concrete produced are by trucks; either heavy trucks or medium heavy trucks except for the transport of cement to depot, which is by ship. Cement and admixtures are both transported by heavy trucks. Aggregate, i.e. macadam and gravel, is often produced in the vicinity of the concrete factory and is therefore transported by a medium heavy truck. Ready-mixed concrete is transported in a liquid-concrete carrier, which is assumed to have the same characteristics as a medium heavy truck. All transport distances are estimated (***Table 9***). Data for the vehicles used are presented in APPENDIX A – LCI data.

Table 9 Transport operations

Transported goods	*Vehicle*	*Distance (km)*
Cement (to depot from cement factory)	Medium ship	800
Cement (to concrete plant from depot)	Heavy truck	50
Macadam (to concrete plant)	Medium heavy	20
Gravel (to concrete plant)	Medium heavy	20
Superplasticizer (to concrete plant)	Heavy truck	50
Concrete (fromconcrete plant)	Medium heavy	100

5 LIFE CYCLE IMPACT ASSESSMENT

The characterisation indicators used in this section is presented in APPENDIX E – Characterisation indicators.

5.1 Global Warming Potential

The production of the raw material is the main contributor to the global warming potential (GWP) in the concrete life cycle (***Figure 7***). It causes approximately 85 % of the total GWP. Within raw materials, cement production causes the largest greenhouse-gas emissions due to the calcination process in the cement factory (***Figure 8***). Approximately 69 % of the CO_2 emissions from the factory come from the calcination and the remaining 31 % come from the fossil fuels used (see APPENDIX D).

The calcination process is necessary since it is the clinker mineral that reacts in the hydration process. But it is possible to replace a part of the clinker mineral by ground limestone that is not calcinated. This cement is on the market and is called "construction cement".[62] Another way of reducing CO_2 emissions is to replace fossil fuels by renewable fuels.

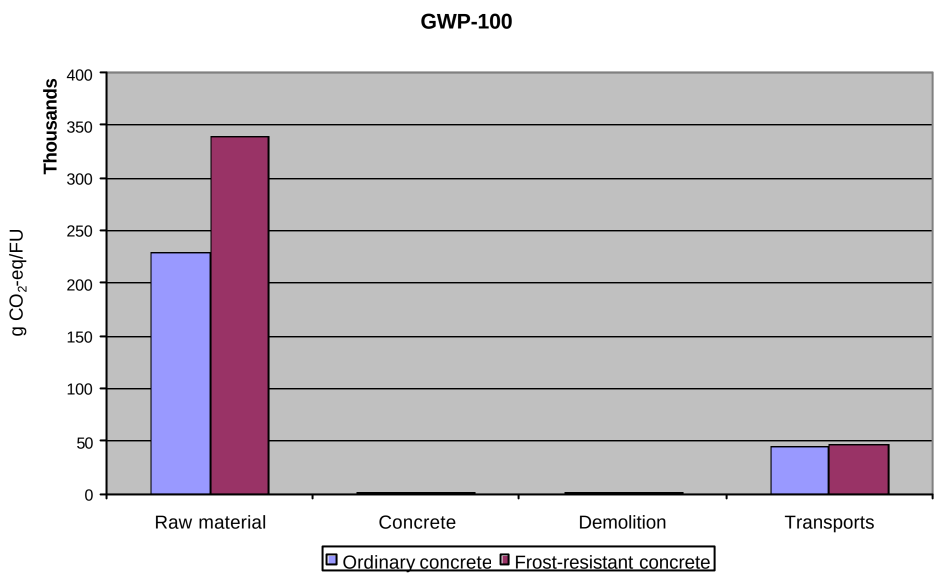

Figure 7 Global warming potential for concrete life cycle steps [g CO2-eq/FU]

[62] Cementa – *Byggcement*, [2005-01-25]

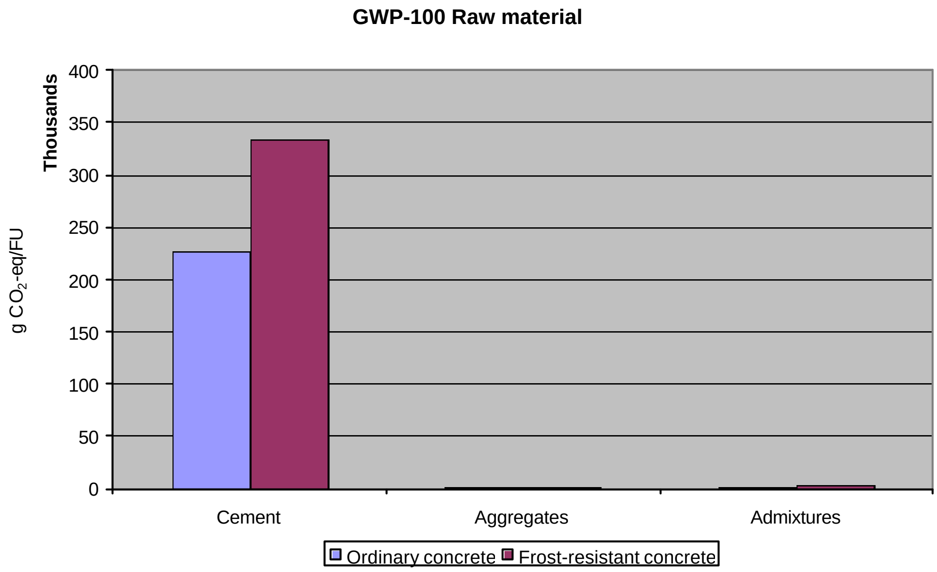

Figure 8 Global warming potential for raw material [g CO2-eq/FU]

5.2 Eutrophication Potential

Transports are the main contributor to the eutrophication potential (EP) (***Figure 9***), approximately 59-65 % of the total EP, and the reason for this is foremost the transportation of the concrete, followed by the transportation of cement from factory to depot. Also the production of the raw material has a significant impact on the EP, mostly because of the production of cement, which causes high emissions of NO_x.

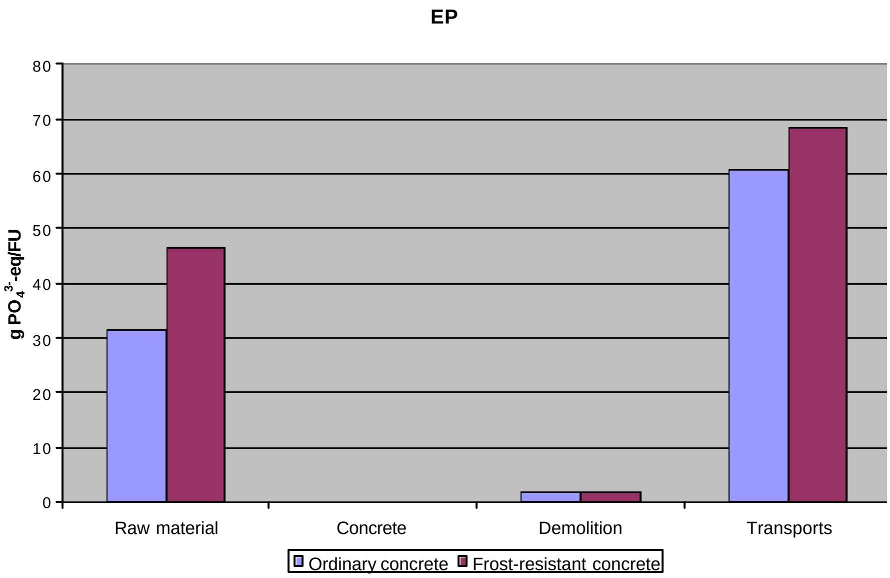

Figure 9 Eutrophication potential for concrete life cycle steps [g PO_4^{3-}-eq/FU]

5.3 Acidification Potential

Transports contribute approximately 61-66 % to the total acidification potential (AP) (***Figure 10***). The transport of concrete has the highest impact, closely followed by the transport of cement from factory to depot. The production of raw materials also contributes to the AP, mainly in the production of cement.

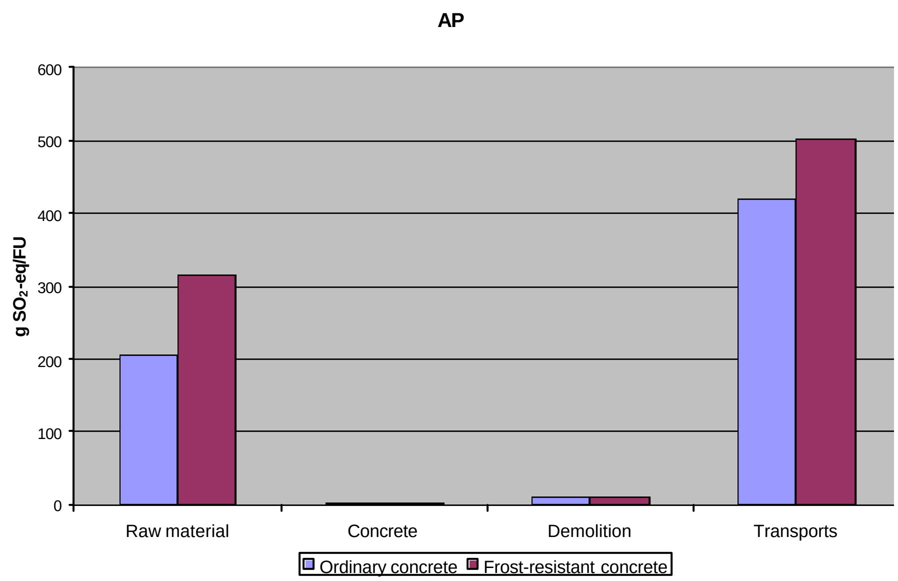

Figure 10 Acidification potential for concrete life cycle steps [g SO_2-eq/FU]

5.4 Photochemical Oxidant Creation Potential

Transports are also the main contributor to the photochemical oxidant creation potential (POCP) (***Figure 11***), namely, by 58-68 % and of this the transportation of the concrete has the highest impact. Of the impact due to raw material production it is the production of the cement (64-76 % of the raw material production) and the superplasticizers (20-25 % of the raw material production) that are the main contributors.

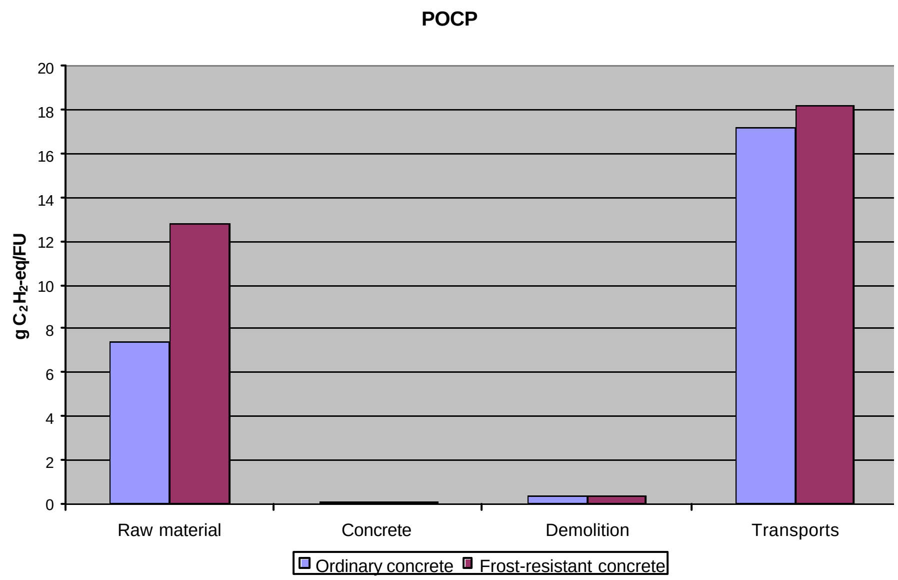

Figure 11 Photochemical Oxidant Creation potential for concrete life cycle steps [g C_2H_2/FU]

5.5 Energy consumption

Cement production has the highest energy demand both as electricity and fossil fuels. Superplasticizers use 2 % of both electricity and fossil fuel in ordinary concrete and 4 % of electricity and 3 % fossil fuel in frost-resistant concrete.

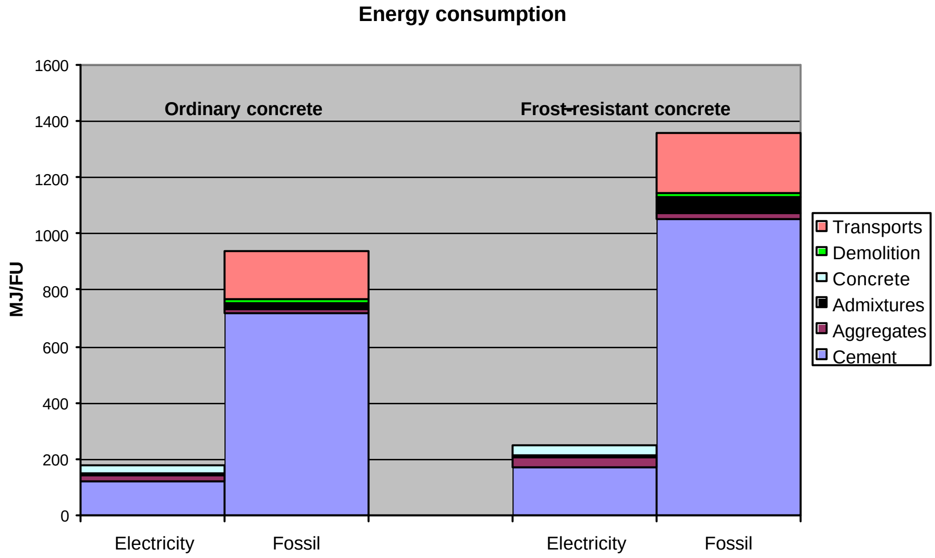

Figure 12 Energy demand for the production of ordinary and frost-resistant concrete [MJ/FU].

5.6 Toxicity

The European Federation of Concrete Admixture Associations has made a study regarding the impact of concrete admixtures on the environment. The authors identified the greatest pollution as originating in "emissions from concrete demolition material". Wastewater treatment and appropriate handling can avoid other sources. [63]

The study shows that approximately 15-25 % of sulphonated naphthalene polymers (SNP), lignosulphonate and polycarboxylates and 30-60 % of sulphonated melamine polymers (SMP) were leached in a worst-case scenario. This might seem much but in an additional test they established that it is only a part of the total leached organic substances that comes from superplasticizers, the rest comes from other products used in the construction such as coatings and adhesives. It is not the original products which are leached but their degradation products, i.e. if SNP are used then it will be mostly naphthalene sulphonate monomers which are leached. The degradation products are more biodegradable than the original substances. The conclusion of the study is that leakages of superplasticizers from crushed concrete will not cause any adverse effects on humans or the environment if the superplasticizer and the product are handled correctly. Concrete admixtures are water-soluble and will not accumulate in, for example, soils and organisms.[64]

A study by Togerö[65] shows that there is a small fraction of formaldehyde in both SNF and SMF (less than 0.3 %). Formaldehyde is hazardous both to water organisms and to humans. It is strongly allergenic and in large amounts carcinogenic. The conclusion of the study is that the emission of formaldehyde from concrete is low.

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[63] Mäder et al., 2004
[64] ibid
[65] Togerö, 2004

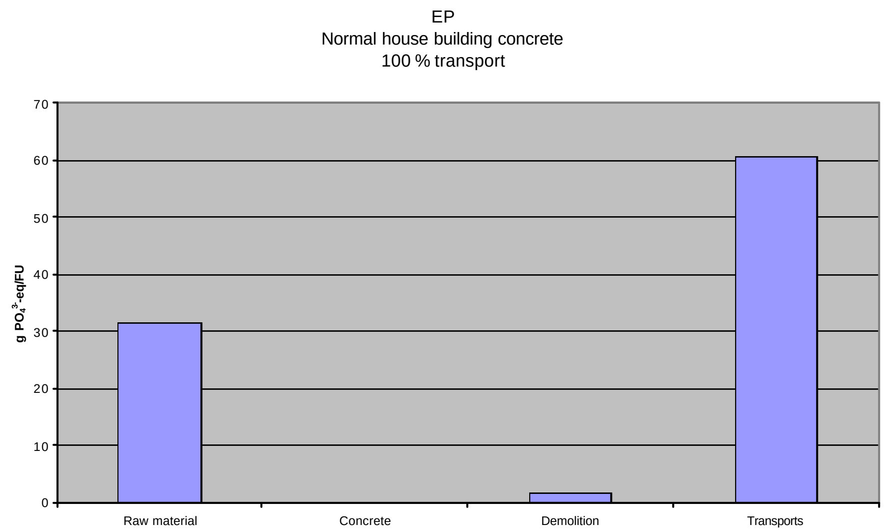
Another study, by Dransfield[66], presents similar conclusions but gives a warning when the concrete is in contact with drinking water, because of the presence of formaldehyde. The study cannot however, in a worst-case scenario, show a significant health risk from leaching of admixtures from concrete.

[66] Dransfield, [2005-05-30]

6 TRANSPORT DISTANCES

Since it is the transport distances that is one of the main contributors to the total environmental impact from concrete it is an important factor to evaluate to see if the outcome changes when the transport distances vary.

Calculations show that there is a linear ratio between transport distances and environmental impact, see APPENDIX G – Transport distances. When calculating with the transport distances used in this study, the transport operations stand for twice as much environmental impact as the raw material production. If the transport distances are reduced by 40 % the environmental impact between raw material production and transports becomes almost equal, only 10 % difference, see ***Figure 13***. This shows how important it is to have good estimations to get a fair result. The calculation is done on normal concrete for house construction and the eutrophication potential but the result is similar for frost-resistant concrete and also when AP and POCP is looked at.



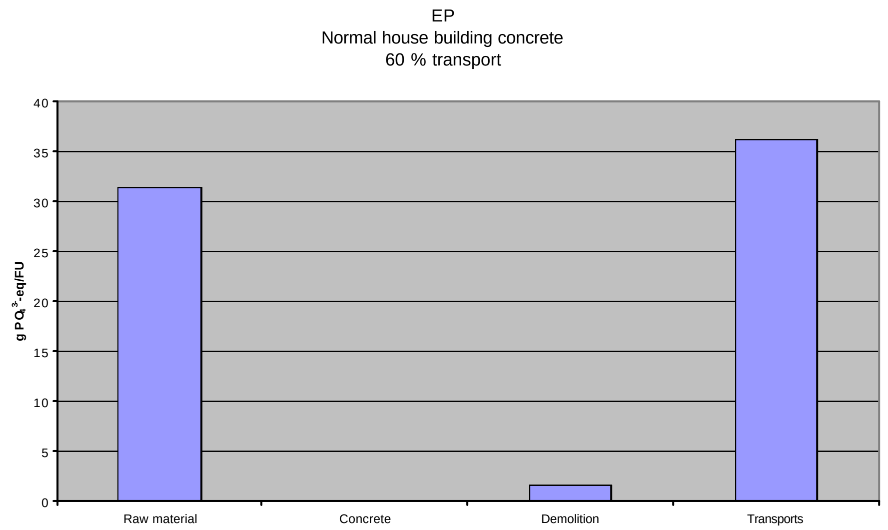


Figure 13 Difference between raw material production and transport when the transport distances are reduced by 40 %.

7 COMPARISON WITH PREVIOUS STUDIES

Cement production is the main source to the environmental impact from the raw material production. Therefore a comparison between the impact from cement production in 1995 (based on data from Björklund & Tillman[67] and Vold & Rønning[68]) and the production in 2005 (based on this study) where done.

The comparison clearly shows that the environmental load from cement production has decreased during the last ten years (***Figure 14***). The GWP has changed least, with a reduction of approximately 6 % and the POCP has the highest reduction, approximately 80 %. The reduction in GWP is mainly because of the replacement of a part of the fossil fuels to alternative fuels. Much waste is used as fuels in cement production. The reason for the large reduction in POCP is probably that the incineration of fuel and the cleaning of emissions have improved over the ten-year period. Emissions of HC are 1 % of the emissions in 1995. The reason for the decrease in AP is a more effective sulphur removal in the production. There was five times as much SO_x emission from cement production in 1995 as in 2005. The reduction in EP is due to lower emissions of NO_x, of which today's emission is only 1/3 of that in 1995. The comparison can be done since the system boundaries of the both studies are approximately similar. LCI data for cement production in 1995 are presented in APPENDIX F.

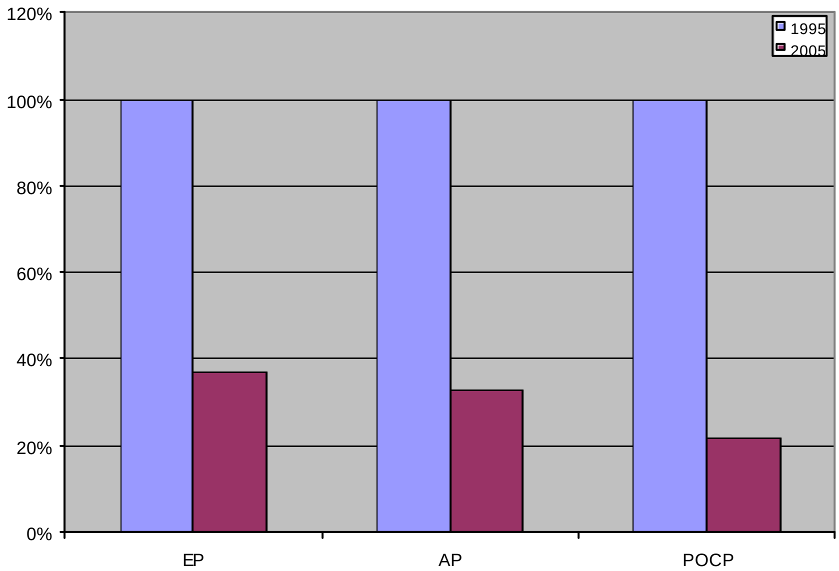


Figure 14 Difference in environmental impact from cement production between year 1995[69] and 2005 (based on this study).

[67] Björklund & Tillman, 1997
[68] Vold & Rønning, 1995
[69] Björklund & Tillman, 1997 and Vold & Rønning, 1995

8 CONCLUSION AND DISCUSSION

This study shows that it is the raw material production (concerning GWP) together with the transportation operations (concerning EP, AP and POCP) that are the main contributors to the environmental impact of concrete (***Figure 15***). Within the transport operations it is the transport of the concrete, by medium-heavy truck, followed by the transport of the cement to the depot, by ship, that make the largest contribution. The evaluation of the transport distances showed that the transportation distances are linearly related to the environmental load. When the transport distances were reduced by 40 % the environmental load from transport operations decreased to approximately the same level as for the raw material production. Since most of the transports of raw material are short, the long transports, such as those above, i.e. transportation of concrete and cement to depot, give large contributions. Transportation by ship has the smallest impact per tonne kilometre and covers the longest distance.

The cement production has the largest impact of the production of the raw materials, and the comparison of the results from this study and a previous LCA study from 1995 indicates that the environmental impact of the cement production has decreased between 60-80 % of the EP, AP and the POCP and 6 % of the GWP over the past ten years. The reasons for this may be the development of better cleaning steps in the production and more effective incineration, together with increased use of renewable fuels. The reason why the GWP has not decreased by more than 6 % has mainly to do with the large impact of the calcination process. The decrease in AP and EP is probably because of the improved sulphur removal, which has been significant in cement production during recent years.

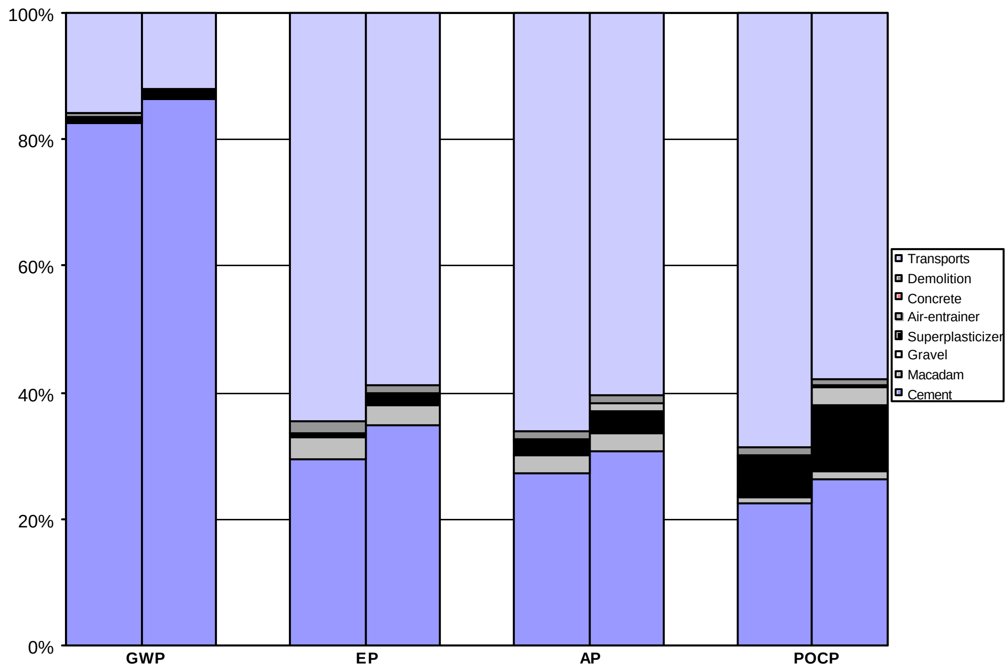


Figure 15 Difference in impact between the different stages in the concrete life cycle. The left-hand column is for ordinary concrete, the right-hand column for frost-resistant concrete.

Superplasticizers make a contribution of 0.4 % of GWP, 0.7 % of EP, 2.1 % of AP and 6.0 % of POCP in ordinary concrete. The corresponding ratios for frost-resistant concrete are 0.6 %, 1.3 %, 3.6 % and 10.4 %. Thus, superplasticizers have a limited environmental impact in concrete and, according to three independent studies, there is only a low risk of toxic effects due to leakage of superplasticizers from demolition materials.

A comparison of macadam and gravel as aggregate in concrete shows that macadam is the better choice when the natural resource aspect is in focus but if the environmental impact is in focus gravel excavation has less impact.

Frost-resistant concrete has a larger environmental impact per m^3 than ordinary concrete since it has a higher content of cement, which is a large contributor in both raw material production and transport operations. Frost-resistant concrete requires 38 % more electricity and 45 % more energy in the form of fossil fuel per m^3 compared to ordinary concrete. The contribution to the GWP, frost-resistant concrete is 41 % higher, to the EP 24 % higher, to the AP 30 % higher and to the POCP 25 % higher per m^3 than ordinary concrete. Even though the frost-resistant concrete has a higher environmental impact and energy demand, these are not the only aspects that have to be considered in construction. Frost-resistant concrete is often used in constructions, such as bridges and dams, which have particularly high requirements in durability.

When the results of this study are compared to a previous LCA study on concrete from 1995 by Vold & Rønning[70], the environmental impact from concrete has decreased somewhat over this ten-year period. In comparison between ordinary concrete and the undefined concrete analysed 1995 all categories of environmental impacts have decreased by between 13-65 %, GWP the least and POCP the most. In comparison with the frost-resistant concrete there has been an increase in the GWP by 20 % but the other environmental categories are reduced by 35-57 %, EP the least and POCP the most. The comparison can be done since the system boundaries of the both studies are approximately similar.

As concluded above, the environmental load from superplasticizers in concrete is small. In the production of superplasticizers, however, crude oil and natural gas are used both as raw material and as fuel. The crude oil utilized is used in equal parts as raw material and as fuel, while less than 0.01 % of the natural gas is used as raw material, the rest as fuel. Thus, to reduce the environmental impact of superplasticizers in the concrete not only the raw materials have to change but also the way of production.

From a system perspective, it is important to bear in mind that adding superplasticizers also leads to indirect environmental benefits since the amount of water needed in the concrete reduces by approximately 30 %, leading to reduced transportation needs of ready-mixed concrete. Without the superplasticizers the concrete would contain approximately 9-11 % of water, compared to 7-9 % with superplasticizers. This reduction may seem small in it self but when considering the volumes of concrete used, it makes a noticeable difference.

[70] Vold & Rønning, 1995

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APPENDIX A – LCI data

Calculations and LCI data for cement production

The amounts of the various ingredients utilized in cement production have been collected from Cementa AB's report.[71] The three main ingredients are limestone, sand and gypsum. Information used in calculations for LCI data for cement production is presented below.

Table A.1 Main ingredients for the production of 1 kg cement

Lime stone	1.4 kg
Sand	70 g
Gypsum[72]	30 g

The impact of limestone quarrying is assumed to be the same as that of macadam production (***Table A.5***).[73]

The impact of sand production is the same as that of gravel production (***Table A.6***).[74]

Fuels used in the production of cement are coal and coke. The emissions from the use of these fuels are presented as a total sum in the production of the cement (***Table A.2***) at the factory. Emissions from the production and distribution of these fuels are calculated separately and both coal and coke are regarded as coal (***Table A.4***).[75] LCI data for gypsum is presented in ***Table A.3***.

Transports of the raw material to the location of cement production are not taken into consideration since most of the raw materials are usually situated in the vicinity of the cement production facility.

LCI data for cement production is presented in ***Table A.2***.

[71] Cementa och Miljön – Verksamhetsåret 2002, 2002
[72] Björklund & Tillman, 1997
[73] Linné, March 2005
[74] Stripple, 2001
[75] Miljöfaktabok för bränslen, 2001

Table A.2 LCI data for the production of 1 kg cement

	Limestone	Sand	Gypsum	Production of cement	Production of coal	Production of coke	Total
Energy (MJ)							
Coal		2.89E-06		1.88*			1.88
Oil		3.14E-05					3.14E-05
Coke				0.50**			0.506
Natural gas		6.73E-07					6.73E-07
Peat		3.26E-07					3.26E-07
Diesel	0.0249		5.01E-04				0.0254
Biofuel		3.26E-06					3.26E-06
Car tyres				0.416***			0.416
Bone meal				0.0109****			0.0109
Electricity	0.0458	7.23E-05	4.80E-04	0.432			0.478
Emissions to air (g)							
CO_2	2.26	0.00220	0.0394	704	6.006	1.62	714
CO	0.00115	2.22E-06	1.50E-04		0.00111	2.98E-04	0.00271
NO_x	0.0194	1.8E-05	6.82E-04	0.64	0.0244	0.00658	0.691
SO_x	0.00111	1.41E-06	7.73E-05	0.04	0.0375	0.0101	0.0888
CH_4	0.00244	1.13E-08			2.06	0.556	2.62
HC	0.00123	1.33E-06	1.04E-04				0.00133
N_2O	1.07E-04	6.94E-08					1.07E-04
Particles	4.13E-04	6.97E-07	5.04E-05	1.1E-04	0.0488	0.0132	0.0625
NH_3	0.0101						0.0101
Emissions to water (g)							
Oil (aq)	1.24E-04	9.71E-09	2.00E-07				1.25E-04
Phenol (aq)		1.38E-08	2.85E-09				1.67E-08

* Energy content for coal: 27.2 MJ/kg (Rydh et al., 2002)
** Energy content for coke: 28.1 MJ/kg (Rydh et al., 2002)
*** Energy content for car tyres: 32 MJ/kg (Åman, May 2005)
**** Energy content for bone meal is the same as for coal (Cementa och Miljön Verksamhetsåret 2002, 2002)

Table A.3 LCI data for the production of 1 kg gypsum[76]

	Unit	
Material use		
Explosives	g	0.2
Gypsum	kg	1
Energy use		
Electricity	MJ	1.59E-02
Diesel	MJ	1.66E-02
Emissions to air		
CO	g	4.98E-03
CO_2	g	1.31E+00
HC	g	3.45E-03
NO_x	g	2.26E-02
Particles	g	1.67E-03
SO_2	g	2.56E-03
Emissions to water		
COD	g	1.94E-05
Oil (aq)	g	6.64E-06
Phenol	g	9.46E-08
Tot-N	g	3.17E-06

[76] Björklund & Tillman, 1997

Table A.4 LCI data for the production of 1 MJ of coal / coke[77]

	Unit	
Emissions to air		
NO_x	g	0.013
SO_x	g	0.02
CO	mg	0.59
CO_2	g	3.2
CH_4	g	1.1
Particles	g	0.026

[77] Miljöfaktabok för bränslen, 2001

Calculations and LCI data for macadam production

Diesel is used for internal transports, approximately 0.5 L/ton macadam while the stone crusher uses electricity, approximately 9 kWh/ton.[78] Information used in calculations of LCI data for macadam is presented below.

Diesel, Mk 1
Diesel density[79]: 815 kg/m^3
Energy content[80]: 43.2 MJ/kg
Calculated diesel consumption: 0.018 MJ/kg macadam

Emissions for diesel production, distribution and usage are taken from ***Table B.2*** and the transports are assumed to be heavy vehicles.

Electricity, Swedish average
Calculated energy consumption: 0.032 MJ/kg macadam (1 kWh = 3.6 MJ)
Emissions for electricity production are taken from ***Table B.1***.

Table A.5 LCI data for the production of 1 kg macadam

	Unit	
Energy		
Diesel	MJ	0.02
Electricity	MJ	0.03
Emissions to air		
CO_2	g	1.6
CO	mg	0.81
NO_x	mg	14
SO_x	mg	0.78
CH_4	mg	1.7
Particles	mg	0.292
HC	mg	0.9
N_2O	mg	0.0758
NH_3	mg	7.13
Emissions to water		
Oil (aq)	mg	0.088
Tot-N (aq)	µg	1.23
Tot-P (aq)	µg	0.176

[78] Linné, March 2005
[79] Miljöfaktabok för bränslen, 2001
[80] ibid

LCI data for gravel production

Table A.6 LCI data for the production of 1 kg gravel (sand)[81]

	Unit	
Energy		
Biomass fuel	MJ	1.08E-04
Oil	MJ	0.00104
Peat	MJ	1.08E-05
Coal	MJ	9.59E-05
Natural gas	MJ	2.23E-05
Uranium	MJ	0.00348
Hydropower	MJ	0.00113
Electricity	MJ	0.0024
Emissions to air		
CO_2	g	0.0728
SO_2	mg	0.0467
NO_x	mg	0.597
Dust	mg	0.0231
CO	mg	0.0736
Radioactive discharge	µg	2.40E-07
Ash	mg	0.168
N_2O	mg	0.0023
HC	mg	0.044
CH_4	µg	0.376
Emissions to water		
Oil (aq)	µg	0.322
Phenol (aq)	µg	0.459
COD	µg	0.967
Tot-N (aq)	µg	0.153
Waste		
Highly radioactive	cm^3	3.36E-06
Medium and low radioactive	cm^3	3.60E-05
Demolition waste	cm^3	3.60E-05

[81] StrippleStripple, 2001

LCI data for production of superplasticizer

Table A.7 LCI data for the production of 1 kg superplasticizer[82]

	Unit	Load
Raw material		
crude oil (feedstock)	kg	0.091
natural gas (feedstock)	kg	1E-04
water	kg	7.4
Energy		
Coal*	MJ	1.7
Crude oil**	MJ	3.2
Natural gas***	MJ	8.2
Electricity	MJ	2.9
Emissions to air		
CO_2	kg	0.69
CO	g	2.1
HC	g	2.2
CH_4	g	1.2
methanol	g	1.1
NO_x	g	3.5
SO_x	g	6.6
benzene	g	0.0026
heavy metals	mg	0.26
nickel (Ni)	mg	0.28
mercury (Hg)	mg	0.01
cadmium (Cd)	µg	9.1
Halon-1301	µg	8
Emissions to water		
barium (ba)	mg	8.8
copper (Cu)	mg	0.28
formaldehyde	g	0.09
nickel (Ni) (aq)	mg	0.28
PAH's	mg	0.023
Waste		
Non-hazardous waste	g	28
Hazardous waste	g	1.8

* Energy content for coal: 27.2 MJ/kg (Rydh et al., 2002)
** Energy content for crude oil: 42.7 MJ/kg (average value) (Rydh et al., 2002)
*** Energy content for natural gas: 51.9 MJ/kg (Rydh et al., 2002)

[82] EFCA Environmental Declaration Superplasticizing Admixtures, 2002

Calculations and LCI data for concrete mixing

In the fabrication of concrete only electricity is used, 32.7 MJ/m^3, while oil is used for heating the plant, 1.5E-05 MJ/m^3 concrete.[83] Information used in calculations for LCI data for concrete mixing is presented below.

Oil
Energy content of oil[84]: 39 GJ/m^3 (average)

Emissions for oil production, distribution and usage are taken from ***Table B.4***.

Electricity, Swedish average
Emissions for electricity production are taken from ***Table B.1***.

Table A.8 LCI data for the mixing of 1 m^3 of concrete

	Unit	
Energy		
Oil	MJ	1.51E-05
Electricity	MJ	32.7
Emissions to air		
NO_x	g	0.491
SO_x	g	0.426
CO	g	0.589
HC	g	0.0949
CO_2	kg	0.256
N_2O	g	0.0232
CH_4	g	1.6
Particles	g	0.0818
NH_3	g	0.0072

[83] Weywadt, March 2005
[84] Rydh et al., 2002

Calculations and LCI data for demolition

The average use of diesel in the stone crusher is 0.2 L/ton ➔0.007 MJ/kg concrete.[85] Information used in calculations for LCI data for crushing of concrete is presented below.

Concrete density: 2400 kg/m^3
Diesel density[86]: 815 kg/m^3
Energy content of diesel[87]: 43.2 MJ/kg

Emissions from the production and distribution of diesel are taken from ***Table B.2*** and emissions from the usage of diesel in the stone crusher are taken from ***Table B.3***.

Table A.9 LCI data for the demolition of 1 kg concrete

	Unit	
Energy		
Diesel	MJ	0.00712
Emissions to air		
CO_2	g	0.538
CO	mg	0.0926
NO_x	mg	5.35
SO_x	mg	0.278
HC	mg	0.313
Particles	mg	0.0854
CH_4	mg	0.0142

[85] Palm, March 2005
[86] Miljöfaktabok för bränslen, 2001
[87] ibid

LCI data for transports

The transportation vehicles used in the study are heavy trailers, medium-heavy trailers and medium-sized ships. Data for the different transportation types are presented in ***Table A.10***, ***Table A.11*** and ***Table A.12***. Data are collected from NTM[88].

Table A.10 LCI data for a heavy trailer

Heavy trailer	Unit	
total weight	ton	60
total load	ton	40
Diesel Mk1	l/10km	4.9
Energy demand (fossil)	MJ/tkm	0.6
Sulphur ratio	ppm	2
Load capacity	%	70
Emissions to air per tkm		
CO_2	g	48
NO_x	g	0.42
HC	g	0.043
PM	mg	6.7
CO	g	0.045
SO_2	g	0.01

Table A.11 LCI data for a medium-heavy trailer

Medium-heavy trailer	Unit	
total weight	ton	24
total load	ton	14
Diesel Mk1	l/10km	3.5
Energy demand (fossil)	MJ/tkm	1.9
Sulphur ratio	ppm	2
Load capacity	%	50
Emissions to air per tkm		
CO_2	kg	0.14
NO_x	g	1.2
HC	g	0.12
PM	g	0.019
CO	g	0.13
SO_2	g	0.034

Table A.12 LCI data for a medium-sized ship

Medium-sized ship	Unit	
Size	dwt	8000-2000
Energy demand (fossil)	MJ/tkm	0.2988
Emissions to air per tkm		
CO_2	g	22
NO_x	g	0.54
HC	g	0.018
PM	g	0.02
CO	g	0.025
SO_2	g	0.36

[88] NTM, Nätverket för Transporter och Miljön, [2005-05-13]

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APPENDIX B – Tables of emissions

Tables of emissions

Table B.1 Environmental load from average Swedish electricity, per MJ[89]

Resources	
Total use of resources, MJ	0.032
Uranium ore, 0,3% U, g	0.71
Uranium ore, 1,6 %, g	0.084
Emissions to air, mg	
NO_x	15
SO_x	13
CO	18
HC	2.9
CO_2	7842
N_2O	0.71
CH_4	49
Particles	2.5
NH_3	0.22
Production of rest products	
Rest products total, mg	13000

[89] Miljöfaktabok för bränslen, 2001

Table B.2 Emissions from the fuel cycle of diesel Mk1[90]

Environmental load per MJ fuel	Production and Distribution	Usage, light vehicle	Usage, heavy vehicle
Energy consumption, MJ			
energy total, MJ	0.06		
Emission to air, mg			
NO_x	31	250	720
SO_x	19	0.48	1.6
CO	2	160	11
HC	33	21	11
CO_2	3500	74000	73000
N_2O	0	4	3
CH_4	2	2	6
Particles	1	25	11
Emissions to water, mg			
Oil (aq)	5		
N (aq)	0.07		
P (aq)	0.01		

Table B.3 Emissions from the diesel engine of the stone crusher, Mk1[91]

Emissions to air	g/MJ diesel
CO_2	72
CO	0.011
NO_x	0.72
SO_2	0.02
HC	0.011
Particles	0.011

[90] Miljöfaktabok för bränslen, 2001
[91] Hansson et al., 1998

Table B.4 Emissions from oil in a heating plant per MJ fuel[92]

	Production and distribution	Usage in heating plant
Renewable energy resources		
Hydropower, MJ	0.0017	
Windpower, MJ	3.10E-06	
Biofuel, g	0.0086	
Non-renewable energy resources		
Crude oil, main flow, g	26	
Crude oil, g	0.55	
Natural gas, g	1	
Coal, g	0.018	
Uranium, g	1.30E-05	
Emissions to air, mg		
NO_x	25	98
SO_x	10	180
CO	2.7	15
HC	3.6	3
CO_2	5900	76000
N_2O	0.044	0.5
CH_4	3.4	0.5
particles	1.5	
NH_3	1.7E-04	0.6
CFC/HCFC	7.6E-07	
$CHCL_3$	2.7E-08	
H_2SO_4	7.6E-07	
HC	7.3	
HCFC-22	3.3E-04	
HCl	0.0057	
HF	0.005	
HFC-134a	1.2E-04	
VOC	1.3	
Waste, g		
Hazardous waste	0.35	
Other waste	2.8	

References

Hansson P-A., Burström A., Norén O. & Bohm M., 1998, *Bestämning av motoremissioner från arbetsmaskiner inom jord- och skogsbruk* Rapport 232, Institutionen för lantbruksteknik, Sveriges Lantbruksuniversitet, Uppsala

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[92] Miljöfaktabok för bränslen, 2001

APPENDIX C – Inventory tables per functional unit

Inventory tables per FU

Presented below are summarized tables for the two types of concrete presented per functional unit (***Table C.1*** and ***Table C.2***). Also data for specific transports are presented here (***Table C.3*** and ***Table C.4***).

Table C.1 Inventory table per FU, ordinary concrete

	Cement	Macadam	Gravel	Super-plasticizer	Concrete	Demolition	Transport	Total
Energy (MJ)								
Coal	561		0.105	2.57				564
Coke	148							148
Diesel	7.49	15				17.1	305	344
Oil	0.00925		1.14		1.51E-05			1.15
Crude oil				4.83				4.83
Peat			0.0118					0.0118
Natural gas			0.0244	12.4				12.4
Electricity	118	22.5	2.62	4.38	32.71			180
Emission to air (g)								
CO_2	211000	1200	79.6	1040	257	1290	43600	258000
CO	0.798	0.608	0.0804	3.17	0.589	0.222	42.6	48.0
NO_x	204	10.3	0.653	5.29	0.491	12.8	466	699
SO_x	26.2	0.587	0.0510	9.97	0.426	0.666	94.5	132
HC	0.393	0.651	0.0481	3.32	0.0949	0.752	38.1	43.4
CH_4	774	1.29	4.11E-04	1.81	1.60	0.0342		779
NH_3	2.97	5.34			0.00720			8.32
N_2O	0.0316	0.0568	0.00251		0.0232			0.114
Particles	18.4	0.219	0.0252		0.0818	0.205	10.1	29.1
Emission to water (g)								
COD	0.0368		0.00106					0.0378
TOT-N	5.43E-04	9.23E-04	1.67E-04			0.00120		0.00283
TOT-P	7.34E-05	1.32E-04				1.71E-04		3.76E-04
Oil (aq)	0.0368	0.0659	3.52E-04			0.0854		0.188
Phenol (aq)	4.93E-06		5.02E-04					5.07E-04

Table C.2 Inventory table per FU, frost-resistant concrete

	Cement	Macadam	Gravel	Super-plasticizer	Air-entraining	Concrete	Demolition	Transport	Total
Energy (MJ)									
Coal	434		0.0794	5.61	1.62				4412
Coke	217								217
Diesel	11.0	18.3					17.1	339	385
Oil	0.0136		0.861			1.51E-05			0.875
Crude oil				10.56	3.04				13.6
Peat			0.00894						0.00894
Natural gas			0.0185	27.06	7.79				34.9
Electricity	174	27.5	1.99	9.57	2.76	32.7			248
Emission to air (g)									
CO_2	310000	1460	60.3	2280	656	257	1290	46100	362000
CO	1.17	0.743	0.0609	6.93	2.00	0.589	0.222	45.4	57.1
NO_x	300	12.5	0.494	11.55	3.33	0.491	12.8	527	868
So_x	38.6	0.717	0.0387	21.78	6.27	0.426	0.666	135	203
HC	0.579	0.795	0.0364	7.26	2.09	0.0949	0.752	40.2	51.8
CH_4	1140	1.58	3.11E-04	3.96	1.14	1.60	0.0342		1150
NH_3	4.37	6.52				0.00720			10.9
N_2O	0.0465	0.0694	0.00190			0.0232			0.141
Particles	27.1	0.267	0.0191			0.0818	0.205	12.3	40.0
Emission to water (g)									
COD	2.67E-04		8.01E-04						0.00107
TOT-N	8.00E-04	0.00113	1.27E-04				0.00120		0.00325
TOT-P	1.08E-04	1.61E-04					1.71E-04		4.40E-04
Oil (aq)	0.0541	0.0805	2.67E-04				0.0854		0.220
Phenol (aq)	7.25E-06		3.80E-04						3.87E-04

Table C.3 Inventory data specific for transports per FU, ordinary concrete

	Cement to depot	**Cement**	**Macadam**	**Gravel**	**Super-plasticizer**	**Concrete**	**Total**
Distance (km)	800	50	20	20	50	100	
Transportation	Medium-sized ship	Heavy trailer	Medium- heavy trailer	Medium- heavy trailer	Heavy trailer	Medium- heavy trailer	
tkm	236	14.8	15	21.9	0.0755	240	
Energy (MJ)	70.5	9.56	28.0	40.9	0.0489	156	305
Emissions to air (g)							
CO_2	5190	708	2040	2970	3.62	32600	43600
NO_x	127	6.12	18	26.2	0.0317	288	466
HC	4.25	0.634	1.80	2.62	0.00325	28.8	38.1
PM	4.72	0.0988	0.285	0.415	5.06E-04	4.56	10.1
CO	5.9	0.664	1.95	2.84	0.00340	31.2	42.6
SO_2	85.0	0.148	0.509	0.743	7.55E-04	8.16	94.5

Table C.4 Inventory data specific for transports per FU, frost-resistant concrete

	Cement to depot	**Cement**	**Macadam**	**Gravel**	**Super-plasticizer**	**Air-entrainer**	**Concrete**	**Total**
Distance (km)	800	50	20	20	50	50	100	
Transportation	Medium-sized ship	Heavy trailer	Medium-heavy trailer	Medium-heavy trailer	Heavy trailer	Heavy trailer	Medium-heavy trailer	
tkm	347	21.7	18.3	16.6	0.165	0.0475	240	
Energy (MJ)	104	14.1	34.3	31.0	0.107	0.0308	156	339
Emissions to air (g)								
CO_2	7640	1040	2490	2250	7.92	2.28	32600	46100
NO_x	187	9.11	22	19.9	0.0693	0.0200	288	527
HC	6.25	0.933	2.20	1.99	0.00710	0.00204	28.8	40.2
PM	6.94	0.145	0.348	0.315	0.00111	3.18E-04	4.56	12.3
CO_2	8.68	0.977	2.38	2.15	0.00743	0.00214	31.2	45.4
SO_2	125	0.217	0.622	0.563	0.00165	4.75E-04	8.16	135

APPENDIX D

– Calcination vs. fossil fuels in a cement factory

Calcination vs. fossil fuels in a cement factory

The first step is to calculate how much CO_2 emissions that come from the use of fossil fuels. Since the total CO_2 emission is known the CO_2 emissions from the calcination can be calculated.

CO_2-emissions per MJ fuel for coal and coke in end use:
Coal[93]: 90.5 g CO_2 / MJ coal
Coke[94]: 102.7 g CO_2 / MJ coke

In order to calculate the CO_2 emissions from coal/coke from reference the weight ratio 3.66:1 between CO_2 and C is used.

Fossil fuel consumption in cement production:

Table D.1 Fossil fuel consumption in cement production

	kg/ton cement[95]	*MJ/kg fuel*[96]	*MJ/ton cement*
Coal	69	27.2	1880
Coke	18	28.1	506

Total CO_2 emissions from fossil fuel:

Table D.2 Total CO_2 emissions from fossil fuel

	kg CO_2/ton cement
Coal	˜ 170
Coke	˜ 52
Total	˜ 222

Total CO_2 emissions from cement production is **704** kg / ton cement (see “production of cement” in ***Table A.2***).

Fossil fuel causes about 31 % of the total CO_2 emissions from a cement factory.

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[93] Gustavsson et al., 1995, Table 1
[94] ibid
[95] Cementa och Miljön – Verksamhetsåret 2002, 2002
[96] Rydh et al., 2002, Table 44

APPENDIX E – Characterisation indicators

Characterisation indicators

Table E.1 Characterisation indicators[97]

	GWP-100 [g CO_2-eq/g]	*EP* [PO_4^{3-}-eq/g]	*AP* [g SO_2-eq/g]	*POCP* [g C_2H_2-eq/g]
Emissions to air				
SO_x			1	
NO_x		0.13	0.696	
NH_3		0.35	1.88	
CO_2	1			
CO				0.032
CH_4	21			0.007
C_2H_2				1
$CHCl_3$	5		0.803	0.004
CFC (”hard”)	4000-17000			
CFC (”soft”)	93-2000			
CFC-11	4000			
HC	11			0.416
Emissions to water				
BOD/COD		0.022		
SO_2			1	
NO_x		0.13	0.696	
NH_3		0.349	1.88	
PO_4^{3-}		1		

References

Rydh C. J., Lindahl M. & Tingström J., 2002, *Livscykelanalys –en metod för miljöbedömning av produkter och tjänster*, Studentlitteratur, Lund

[97] Rydh et al., 2002

APPENDIX F

– LCI data for cement production in 1995

LCI data for cement production in 1995

The LCI data used for cement produced in 1995 are the same as were used in prior LCA studies on cement and concrete. The original data come from a study made in 1995 by Vold and Rønning[98]. Since the data in that study are much aggregated, the LCI data used in the calculations and presented in ***Table F.1*** are taken from a study made by Björklund and Tillman, (1997)[99].

Table F.1 LCI data for the production of 1 kg cement in 1995

	Unit	
Energy		
Coal	MJ	0.861
Oil	MJ	0.223
Coke	MJ	1.52
Diesel	MJ	0.058
Fossil fuel	MJ	0.925
Fuel from waste material	MJ	0.533
Electricity	MJ	0.47
Emissions to air		
CO_2	g	806
CO	g	0.784
NO_x	g	1.94
SO_x	g	0.451
CH_4	g	0.305
HC	g	0.145
N_2O	µg	0.146
Particles	g	0.162
Emissions to water		
Oil (aq)	mg	0.0297
Phenol (aq)	µg	0.423
COD	mg	0.0867
Tot-N (aq)	mg	0.0142

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[99] Björklund & Tillman, 1997

APPENDIX G – Transport distances

Transport distances

In order to examine how sensitive the total environmental impact of concrete is to change if the transport distances vary following figure were done (***Figure G.1***). When reducing the transport distances with 40 % there was a reduction in environmental impact with 40 %, i.e. a linear relationship.

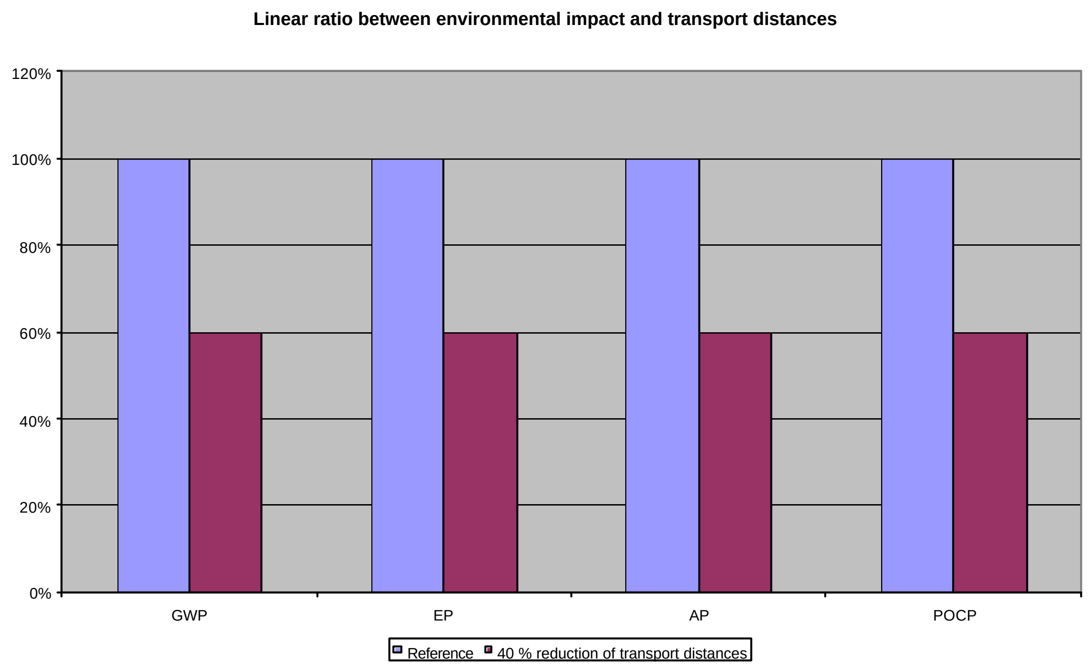

Figure G.1 The relationship between environmental impact and transport distances