

Processing Lignite Fly Ash in Europe

Comparative analysis of the environmental effects of processing lignite fly ash in deposits and in concrete



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Glossary

AW	Adapted Water
CEM I	Ordinary Portland Cement (>95% clinker)
Concrete	Construction material composed of hydraulic binder, aggregates and water
Disposal	Transportation from production site to depositing site
Depositing	Processing waste material into a deposit
Dumping	Transportation from waste material production site to depositing site and processing it into a deposit
FA	Fly Ash
FU	Functional Unit
GGBFS	Ground Granulated Blast Furnace Slag, residue from iron ore ovens
HFA	Hard-coal Fly Ash
ICP-OES	Inductively Coupled Plasma - Optical Emission Spectrometer, used to determine concentrations of a wide range of elements in solution
ICP-MS	Inductively Coupled Plasma - Mass Spectroscopy, used to determine concentrations of specific elements in solution
ISO	International Organization for Standardization
L/S	Liquid / Solid ratio
LCA	Life Cycle Assessment
LFA	Lignite Fly Ash
LT	Long term
Mortar	Construction material composed of hydraulic binder, fine aggregates and water
OPC	Ordinary Portland Cement (>95% clinker)
Paste	Construction material composed of hydraulic binder and water
Prism	Beam from 40mm x 40mm x 160mm
ST	Short term
Tonne	Metric ton
Tkm	Tonne/km

Abstract

This study investigates environmental impacts of processing of lignite fly ash (LFA) in Europe. Lignite fly ash is a waste product from lignite-fired electricity production. Currently 95% of LFA is dumped in depleted lignite mines. However, there are alternatives. In this study the differences between two main processing options are examined. First, the environmental impacts of dumping LFA, which is a reference situation, are researched. Secondly, an alternative scenario of processing of LFA in concrete is researched. In order to see if utilization of LFA in concrete is a realistic possibility, LFA-concrete has been constructed. LFA samples from different production sites throughout Europe have been collected and characterized. These samples have been used to construct the LFA-concrete and research the leaching behavior of LFA deposits.

In addition to assessment of the two main processing options, an indicative research on processing of LFA in geopolymers has been done. The geopolymer concept is an innovative approach in which polymer bonds are created to form a concrete-like material. This third processing alternative is however not an integrated part of the difference analysis and will be addressed separately.

In order to determine the environmental impact of the processing options this study follows the standard protocol of life cycle assessment (LCA).

The results show that there is a large variation in composition between the different types of LFA. As a consequence, there are differences in leaching behavior and strength development when processed in concrete. Although the LFA-concrete developed less strength than the reference concrete, 5 out of the 6 samples that were tested achieved over 90% of the reference compressive strength when replacing 15% of the cement with LFA. Due to the high uncertainty in both the emissions of dumping LFA and the effects of these emissions, it is hard to make a judgment about the extent of the overall adverse environmental effect. It can be concluded that processing of LFA in concrete reduces the environmental impact. The prevention of dumping of LFA and decrease in consumption of cement in concrete are the main sources of this reduction.

Initial indicative results of the geopolymer research show great promise. The strength development of some LFA-geopolymer-concretes exceeded expectation. To discover full potential of utilization of LFA in geopolymers more research is necessary.

Preface

Context

This Master thesis is done within the Energy & Resources track of the Sustainable Development Master, at the University of Utrecht. The program of the Energy & Resources track focuses on sustainable use and production of energy and materials. Improving efficiency of use of energy and resources, along with assessing and preventing adverse environmental effects caused by the use of energy and resources are the most important topics within the program. Burning of fossil fuels is regarded as the main cause of the environmental problems. Within the spectrum of fossil fuels, lignite is considered as one of the most polluting. Furthermore, the production of building materials such as concrete also causes significant pollution. In this study, a method to diminish some of these environmental problems, will be researched. The fundamental topics that play an important role in the Energy & Resources program will return in this research.

Acknowledgements

In order to conduct this research the cooperation from third parties was required. Information, research facilities and material have been provided by several parties. Special recognition is expressed to the following actors:

B|A|S, Venlo, Netherlands

The largest fraction of the experimental research has been conducted at B|A|S research and technology. B|A|S is an independent research institute which is specialized in researching the characteristics of building materials. During the research period I had an internship for two days a week at B|A|S in which the practical testing work could be executed. Thus, the characteristics of the LFA building materials have been tested at B|A|S in Venlo. These tests give independent information about the material characteristics. Within the organization there's a large amount of expertise on the characteristics and testing methods of building materials. The laboratory tests that are conducted at B|A|S have provided essential information about material characteristics. These tests are described in the inventory section. Results of these tests are used to compare application possibilities of conventional building materials with those of LFA building materials.

I would like to express special thanks to Toine van Casteren, Director of B|A|S, and Marique Ruijs who has been my personal internship supervisor.

Evert Nieuwlaar, University Utrecht

Evert Nieuwlaar was my personal supervisor for this research. He provided highly valuable feedback and guided the research in the right direction. Especially his specialism in LCA research was helpful in developing the adequate methodology.

Geolab, University Utrecht

The leaching tests were conducted in the Geolab at the University Utrecht. This lab has the facility to conduct shake tests and measure the leachate with ICP-OES for main elements and ICP-MS for trace elements.

Henk Nugteren, University Delft

Henk Nugteren works on development of Geopolymers from fly ashes. He has participated in finding alternative ways of processing of LFA. Under the supervision of Henk Nugteren geopolymers from LFA were constructed in the laboratory of the TU in Delft.

Rob Comans, ECN

Rob Comans is a specialist on leaching of fly ashes. He assisted the leaching research and helped developing the methodology. Outcomes of the research and chemical processes that occurred were discussed thoroughly with Mr. Comans.

Electricity companies

There has been contact with various electricity companies. The following companies provided the LFA samples:

1. RWE, Germany: They provided a visit to a power plant, strip mine and ash deposit. Contact persons were Mr. Knapp and Mr. Spicker.
2. EON, Germany: They also provided a visit to a power plant. Contact person was Mr. Lorenz.
3. MUEG: They have the task to process the ashes of EON and provided for me to see this process. Contact person was Mr. Schmeiser.
4. ČEZ, Czech republic: Contact person was Mr. Donát.
5. Public Power Co, Greece: Contact person was Mr. Passalidis

There were two other parties that provided LFA:

1. Brown Coal Research Institute, Czech republic: Contact person was Mr. Sasek, Ph.D.
2. Kremer Baustoff, Czech republic: A commercial company that sells LFA. Contact person was Mr. Czoske

I would like to thank all these actors for their involvement and contribution to this research.

1 Introduction

1.1 Problem definition

With a threatening scarcity of resources and ever increasing environmental problems, the conventional view on material streams has been extensively criticized. The production of materials for utilization in various industries creates pollution and puts pressure on natural resources. Furthermore the increasing amount of waste material creates a number of environmental problems. At the same time a lot of the materials that used to be considered as waste, now provide an essential function in material streams. As raw materials become more scarce this trend will continue, introducing a new view on material streams. There are still a lot of areas where recycling of waste material can become an economically and environmentally sound option. This study will research the possibilities to convert lignite fly ash (LFA), a waste product from lignite-fired power plants, into an industrially valuable material that can help reducing the environmental problems. Ashes from coal-fired power plant are already commonly used in the cement and concrete industry. In this way a part of the Portland cement, a product that causes significant greenhouse gas emissions, can be replaced.

Currently in most European countries about 95% of the hard-coal ashes are processed in the building industry. This is not the case with lignite ashes, of which 40 million tonne are produced annually in the European Union, but only about 5% is currently utilized as a building material (Ecoinvent 2007). It will be a challenge to convert this huge amount of ashes from lignite-fired power plants into a useful building material which could replace some of the cement that is currently in high demand. Converting the LFA into a useful resource for concrete production would diminish the amount of LFA waste and reduce the demand for cement. This could offer a potential environmental benefit.

Research questions

What is the difference in the environmental impacts between processing LFA in deposits and in concrete within the European context?

This is the central question of the research. Three LFA processing options will be researched. The main part of this research will focus on the two main processing options: dumping of LFA in deposits and processing in concrete. At the moment these are the main, most realistic options to process the large amounts of LFA currently produced. The third, more innovative option research is called geopolymers, which consists of constructing concrete-like building materials from waste materials (see § 2.2). A separate chapter is devoted to assess the potential of processing LFA in geopolymers. The research that is done on LFA-geopolymers should give an indication on the potential of the material and the environmental profile of its production.

Because processing of LFA in concrete is not yet a common practice, it is valuable to research potential of this practice. Therefore the second research question is:

What is the potential of processing LFA in concrete in Europe?

Assessing the potential of LFA in concrete is dependent of many different factors. This makes it complex to make quantitative statements about this potential. Therefore only the factors that determine this potential, and their relations, will be addressed in this research.

Up to this moment the research on LFA has been fragmented, which made it difficult to assess the potential. There are already several researches on LFA processing. The leach behavior of several types of LFA has been researched (GEORGAKOPOULOS, FILIPPIDIS et al. 2002),(Mitra, Ram et al. 2007),(Mudd, Weaver et al. 1998). Furthermore the following studies about the function of LFA in concrete were published (Koukouzas, Vassilatos et al. 2005) and (Mallmann 2002). The results of these studies are however hard to compare, because all authors use different types of LFA, apply different methodologies, produce different types of results and emphasize on different elements. Furthermore no studies which used an LCA approach to determine the environmental impacts of processing of LFA were found. The combined results of other studies didn't provide the information needed to answer the research questions. This is why based on the different methods used in other studies the research methodology to conduct this research was developed. With the same types of selected LFA every processing option is tested and evaluated. This ensures comparable results.

During this research the current problems with regulations, European standards and environmental assessment methods will try to be identified.

1.2 Objective and scope

Determining the difference in the environmental impacts between processing LFA in deposits and in concrete is the main objective of this research. If this difference is known, involved actors can make better decisions about processing LFA streams.

In order to assess the applicability, the technical characteristics of LFA in concrete will be assessed. In order to test this, different concrete recipes will be made. Both conventional and innovative ways of constructing concrete will be assessed.

The scope of this research is LFA production and usage within the EU-27. There are several reasons to this. First, restriction of the research to the EU is based on availability of information. Within Europe there is relatively good data on LFA processing and production of building materials. There are different methods of LFA processing in the European countries. Investigating the different impacts of these methods will provide useful information in the decision making process.

Secondly, the European Union is chosen as the research area because of the ever increasing environmental regulation from the EU. The EU has the capacity to construct a guideline on the processing of LFA; uniform European policy can be developed.

Within Europe the main lignite producing areas have to be identified. The results of this study can be used as a reference in the evaluation of ash processing policies of governments, electricity companies and producers of building material.

1.3 Methods

To assess the environmental impact of the two LFA processing scenarios, several research methods will be used. First of all, the LFA from various locations will be characterized. This is done by comparing the physical and chemical composition of LFA from different locations and make groups of LFA with similar characteristics. In this way the amount of LFA types included in further research can be limited. Furthermore LFA from locations that were not included in this research, can be compared with the composition of the researched LFA. If the compositions are comparable it could give an indication on the processability. To assess the option of processing LFA in concrete, first of all the technical potential of LFA-concrete has to be researched. This will be done by producing a concrete of which the recipe is adapted by excluding a percentage of the cement weight and replacing that with LFA. Normal concrete contains cement, sand, gravel and water. Because the gravel doesn't contribute to the strength development of the concrete, a mortar is used to conduct the tests. A mortar is in fact a concrete without gravel, and is easier to produce and test. The standards that will be used to test the strength development of LFA, prescribe the use of mortar. Before the mortar is poured, the consistency has to be tested to ensure that the LFA-concrete can be processed in the same way as conventional concrete. After the mortar hardens out the strength will be measured at two predetermined periods; 28 and 90 days. Both flexural and compressive strength of the mortar will be tested. The results of these tests will be compared with a reference mortar produced with CEM I that will be tested in the same way. After these tests are done, the technical performance of the LFA can be determined. This can then be compared with the performance of the reference mixture. If the technical performance of the mortars is similar, a comparison on environmental performance can be made.

Besides constructing mortar in which a percentage of cement is replaced with LFA, geopolymer-concrete is going to be constructed as well. The geopolymer concept is an innovative approach in which polymer bonds are created to form a concrete-like material. Simple experiments will be done to assess the potential of processing LFA in geopolymer-concrete. Because this is the first time LFA will be used to create geopolymer-concrete, no projections about the correct recipe and outcomes of the tests can be done. This is why only indicative tests will be performed.

The environmental performance of the different processing options can be assessed with life cycle assessment (LCA). With this data analysis tool, the emissions of the production processes of the used materials can be translated in environmental impacts.

First of all the impacts of depositing LFA will be determined. Before the environmental impacts can be calculated, the emissions of depositing will have to be determined. Different types of leaching tests are going to be performed to simulate the expected leaching within different time frames. The results of these tests are required to determine the emissions of the reference situation in which LFA is deposited. In order to determine the environmental profile of processing LFA in concrete, the differences with producing conventional concrete will be analyzed. The ingredients of geopolymers will also be analyzed with LCA to assess if this is an environmental sound option.

After the LCA has been done and the environmental impact of the different processing options is known, conclusions about the processing options can be made.

Besides using these methods to generate the results that are needed to assess the different processing options, the methods and norms themselves will also be critically assessed.

1.4 Structure

To gain insight in the topic of LFA, in chapter two background information on production, processing and geographical scope of LFA in Europe will be given. This will provide background information used in the rest of the text. Chapter three outlines in detail the research methods that were used to answer the two research questions. Next, in chapter four the results of characterization tests are presented. After that chapter five will show the results of the applicability tests are given in chapter five. In chapter six the environmental impacts of the two main processing options are assessed. A separate chapter seven is devoted to assessing of the potential of processing of LFA in geopolymer-concrete. In this chapter the research methods, results and environmental impact of geopolymer-concrete will be addressed. In chapter eight the comparison of environmental profiles of different types of concrete is made. The broader potential of these different types of concrete is addressed in chapter nine. The discussion, in which the rigidity of the results is treated, is presented in chapter ten. Finally, the conclusion to this thesis and recommendations are given in chapter eleven.

2 LFA; a general description

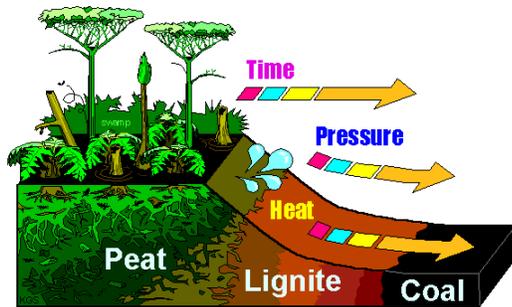


FIGURE 1 NATURAL LIGNITE DEVELOPMENT

Lignite fly ash (LFA) is a byproduct of lignite-fired power plants. Lignite (also referred to as brown coal) is a coal type which has a low heating value (10-20 MJ), and a high moisture and ash content. Lignite is formed from peat that is exposed to pressure and heat (Figure 1) over long periods of time. The longer the exposure period, the lower the moisture and ash content of the resulting coal and the higher its fuel quality. Lignite is a young type of coal, and is therefore considered to be of a low-rank fuel quality.

Lignite is not a homogeneous product. There are quality variations within and between the lignite layers (Adamidou, Kassoli-Fournaraki et al. 2007). These differences also translate in the LFA quantities and composition. Large variations in the composition make processing more complicated. To control the burning process within the lignite power plant a constant blend of various lignite qualities is fed into the plant. This consequently also ensures a more constant composition of the LFA.

After burning the lignite for electricity, LFA is produced; this is considered a waste product. Although the production of LFA is considered a problem, there are possibly useful applications in the building industry. This research will address a possible solution for two problems: the environmental impact that is created by depositing LFA and the environmental impact that is created by the cement industry. Using the LFA as a building material has two advantages:

1. The LFA that is used as a building material doesn't have to be dumped in the deposits. The environmental impact from depositing LFA is prevented.
2. LFA can replace cement. Production of cement has several impacts on the environment. By using LFA instead of cement, the pollution caused by the cement production process can be reduced.

Currently only a few percent of the LFA that is produced in the lignite fired power plants is used in the building industry. In most countries the LFA is disposed in the lignite mines (Ecoinvent 2007). This can cause various environmental impacts. Wind can erode LFA deposits, harmful particles are blown into the environment. Furthermore the leaching of polluting substances to the soil and groundwater is considered a problem (Mitra, Ram et al. 2007).

2.1 Production of LFA

The total European production of lignite was 320 million tonne in 2005, of which 300 million tonne are produced in the power generation (EIA 2005). The ash content of the lignite can differ, depending on the country of origin. Lignite that has a high quality and thus high caloric value will have a low ash content. Rhenish lignite from Poland for instance has an average ash content of 7%, whereas Greek lignite can have an ash content up to 20% in natural (wet based) coal, which is about 40% on a dry basis (Ecoinvent 2007). In this case it means that 50% of the mined lignite

consists of moisture, 20% consists of inorganic material (ash) that will not burn, and 30% of organic material that will burn up and provide the required energy. The moisture content of the lignite can be as high as 60% (Kovács 2002).

Therefore, from the total amount of lignite produced in the EU, the total ash content within the EU amounts to about 50 million tonne per annum. This is based on an assumed average ash content in the natural coal of about 15%. However, with LFA having a typical share of 80% of the ashes (§4.2), it seems there is significantly more of LFA (around 40 million tonne) produced yearly. The adverse environmental impacts of disposal of these amounts of LFA are considerable, as will be discussed in detail later in the text (Mitra, Ram et al. 2007).

2.1.1 Process characterization

Lignite is fired in the same way as hard-coal. In Figure 2 the schematics of a typical coal-fired power plant is presented.

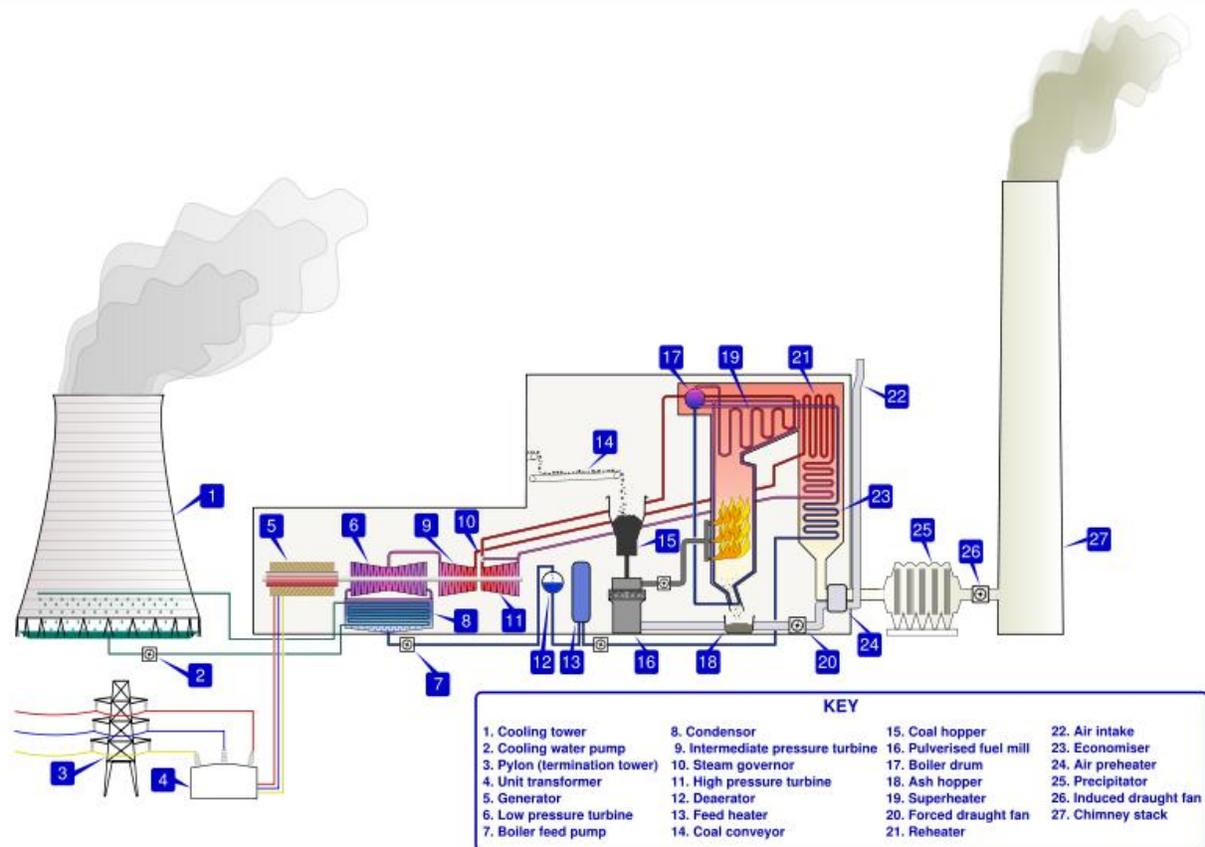


FIGURE 2 SCHEMATIC OF A TYPICAL COAL-FIRED POWER PLANT

Part of the lignite is inorganic and will not burn up. This fraction forms the ashes. The ashes can be subdivided into two fractions, fly ashes and bottom ashes.

1. Fly ashes are the fine solids that are carried in the flue gasses (smoke). The fly ashes are filtered out by electrostatic precipitators to prevent them coming in the open air and the environment (see number 25 of Figure 2). The precipitators are shaken at distinctive intervals and the FA falls into a silo before it is transported for processing. Depending on

the temperature, particles melt together to form glass particles. These glass particles are important for the binding function of the FA. This will be explained in § 2.2.2.

2. Bottom ashes are the solids that remain on the bottom of the boiler (see number 18 of Figure 2). The bottom ashes form the larger fraction of the ashes. Because of their size and composition they are less interesting for the building industry.

The ratio between fly and bottom ashes depends on the quality of the lignite and the firing method of the power plant. Typically between 60% and 90% of all ashes are fly ashes.

2.2 Processing of LFA

There are various options for processing LFA. Currently the largest part of LFA is dumped (Ecoinvent 2007), but there are other options.

Research indicates successful, beneficial application of LFA in production of concrete, bricks, wood substitute products. Additionally, in the past LFA was applied in roads for replacement of cement, soil stabilization and consolidation, road base/embankments, and land reclamation (Haynes 2009). However processing of LFA in concrete seems to be the most interesting option. The chemical

reaction that occurs when LFA is mixed in fresh concrete could contribute to the strength of the resulting mixture. The application of a specific type of Greek LFA in concrete has been studied (Koukouzas, Vassilatos et al. 2005) and showed potential. In other applications the LFA acts more as filler. Its physical characteristics contribute to the function of the application, but in most cases there is no chemical reaction that contributes to the function of the application. With the application



FIGURE 3 SCIENTIFIC PAPERS ON FLY ASH APPLICATION

of LFA in concrete both the chemical and physical characteristics contribute to the function of the actual product. This is probably why within fly ash literature most research is focused on application in concrete (Figure 3). Because of the large variety in physical and chemical characteristics of LFA within Europe, more research is needed to identify the application opportunities for the various types of LFA. Each type of LFA could have a specific application field in which it has the best function. The optimal recipes for utilization of LFA in concrete also need further research.

Unfortunately until today the above-mentioned alternatives have not become mainstream practices for LFA. Generally, there are several reasons:

1. **Convenience of disposal:** Ashes are a waste product of coal-fired power plants, that are traditionally disposed in old lignite mines located as a rule in a vicinity of a lignite-processing power plant. Such disposal is convenient since it does not impose high costs of transportation of the ashes. In contrast, a different situation exists with fly ash from hard coal: hard coal fly ash (HFA) is widely used in the building industry. Such utilization was predominantly stimulated by the fact that most hard coal-fired power plants had to

transport their ashes to a designated depositing site, imposing costs of transportation, land-filling, and environmental cost of leaching of ashes in the landfill. This is what stimulated research into alternative ways of processing of hard coal ashes, which is not the case with LFA.

2. Variety: There is a large variation in the physical and chemical characteristics of LFA from different locations (Macphee, Taylor et al. 1993). This means that there is no standard type of LFA. This makes it complicated for the industry and requires more research. The variation in physical and chemical characteristics of the HFA is much smaller.
3. Homogeneity: There are geological differences in the composition of lignite coal layers at a specific mine site. These differences have effect on the composition of the LFA. This makes it hard to sell, as the building industry requires continuously homogeneous products.
4. Lack of regulation: Most of the lignite producing areas are situated in former Soviet countries in Eastern Europe. The environmental regulation in these countries is not yet on the same level as in Western Europe.

2.2.1 Dumping

As already discussed, currently the largest fraction of the LFA that is produced is dumped (Ecoinvent 2007). In this research two main dumping steps that cause environmental impacts are distinguished. Disposal: transportation from the lignite-fired power plant towards the depositing site. Depositing: interaction between the deposited LFA and the environment. For the depositing old lignite mines areas are used. There are various disposal methods from the power plant to the ash deposit.

1. Dry transport with a silo truck
2. Dry transport with a silo train.
3. Dry transport with a conveyor belt. Measures to reduce dust have to be taken. This can be done by sprinkling the ashes or closing of the conveyor belt.
4. Wet transport through a pipeline. In most cases the waste water from the desulfurization installation is mixed with the LFA.

These transportation methods will influence the buildup of the deposit. Besides the buildup the depth, local geological conditions, and leaching prevention methods will influence the environmental impact of an LFA deposit. Furthermore the time that the deposit is open for disposal has an effect on the influence of weathering which in turn effects leaching of elements. The effects of leaching of LFA depositing are modeled in this research. Effects of wind erosion have not been modeled and are beyond the scope of this research. The factors that determine the wind erosion are quite complex and there was not enough location specific information about these factors. "The low erosion threshold in a wind tunnel of between 9 to 11 m sec⁻¹ (32 to 40 kmhr⁻¹) indicates that these particles need only a moderate wind velocity to become airborne" (Klose, Tölle et al. 2003). How and where LFA is dispersed is also dependent of various factors. The extent of the problem is hard to assess, but is clear that prevention of these problems does have benefits.

2.2.2 LFA in Concrete

The main focus of this research is the processing of LFA in concrete. Currently most of the HFA is already processed in concrete. Processing of LFA in concrete production seems the most promising option. If fly ash reacts with water and cement it can fulfill a binding function (this will be explained further in this paragraph). Another advantage of processing LFA in concrete is that it reacts and hardens in such a way that leaching and erosion is minimized. Concrete is conventionally built up from aggregates (sand, gravel), water and cement. Different types of cement can be used, but traditionally it is Portland cement, as 95% of all cement produced is of this type (Sjunnesson 2005). This is also the case in this study, whenever cement is mentioned. Portland cement contains more than 95% clinker and is referred to as CEM I. Generally, other types of cement are described in the EN 197-1 standard (appendix 1). CEM II is Portland fly ash cement which can also contain fly ash; the clinker percentage however must be above 65%. However there are other, more rare types of composite cements like CEM V in which the composition is less restricted. There is no technical difference in premixing LFA in the cement or adding it in the recipe of the concrete. Within this study LFA will be seen as an ingredient of concrete, not of composite cement.

The aggregates used in concrete typically consist of sand with particles ranging in diameter from 0.06 mm to 2 mm and gravel, with particles ranging from 2 mm up to 64 mm. The types and amounts of cement, aggregates and water used depend on requirements of the concrete. For some application which can't contain large aggregates mortars are used. A mortar is in fact a concrete without gravel, and is easier to produce and test. Mortars are commonly used in masonry, floors and wall finishing. A paste is a mixture between cement and water it doesn't contain any aggregates.

Cement production

Cement is the most important binder in the industry. Together with steel it causes the largest fraction of environmental impacts within the building industry (Flower and Sanjayan 2007). This is why the initial focus will be on replacing cement with LFA. Almost 3% of world total consumption of primary energy and 6% of greenhouse gas emissions are the result of cement production (Badino 2003). This makes the cement industry one of the main contributors of greenhouse gas emissions, while there is relatively limited political and public attention to this problem (Flower and Sanjayan 2007).

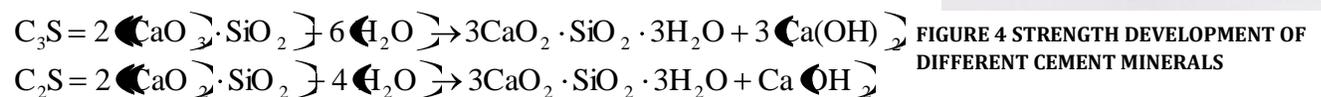
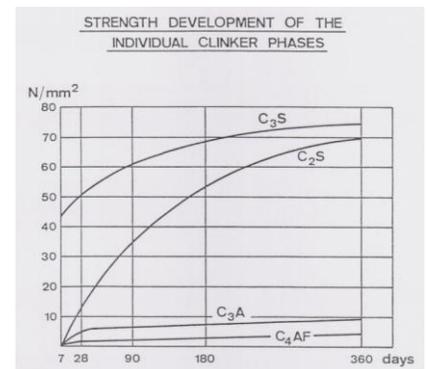
Cement is produced by milling a mix of limestone and clay, which is then burned in a cement kiln. In this way clinker is produced. The clinker is milled with addition of a small percentage of gypsum in order to control the setting time of the clinker.

The clinker production process generates CO₂ in two ways. The first is through the burning of fossil fuels in the cement kiln (1500 °C). The calcination process is the other main contributor to the CO₂ production, accounting for 60% of the total CO₂ production. The chemical process is: $\text{CaCO}_3 + \text{heat} = \text{CaO} + \text{CO}_2$ (Sjunnesson 2005). Furthermore the milling of the clinker also requires energy and thus produces CO₂.

The European cement production (EU27 countries) is estimated at 286 million tonne in 2007. This is about 10% of the global production. The main producing countries are Spain, Italy and Germany. The cement consumption in Europe, including Turkey, is estimated at just over 310 million tonne in 2007, which is an increase of 2.75% in comparison to 2006. It is expected that the European demand for cement will increase even further in the future. New infrastructure and housing programs in Eastern Europe are the main drivers of this growing demand (Song 2008).

Chemical background

To understand how the concrete ingredients react to form concrete, the chemical interaction between the ingredients has to be known. The cement is composed of cement minerals like C_3S and C_2S . When these cement minerals react with water, they will solute and form long chained amorphous structures with the water. Cement minerals production process of cement is steered towards maximizing the fraction of C_3S which is the strongest and fastest reacting cement mineral (Figure 4). Below the chemical reactions of C_3S and C_2S are presented.



Cement Reaction (Ruijs 2005)

These cement structures bond the aggregates (sand and gravel) to form concrete structures. Besides the conventional concrete ingredients, rest products of other production processes are commonly used in concrete. Fly ashes can contribute in the strength development of the concrete in the following way:

Fly ashes can be divided in two main categories (Moreno, Querol et al. 2005):

1. C group: This group has a relatively high $\text{CaO} > 10\%$ and a low $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 < 70\%$ content. It has cementitious properties and can be described as latent hydraulic binders. The hydraulic reaction occurs relatively slowly because the CaO content is still much lower than in cement. Therefore an activator is necessary to speed up the reaction. Cement can be an activator because its reaction products create a high pH value (basic/alkaline) due to its reaction product calcium hydroxide Ca(OH)_2 . Other basic activators can be added as well to increase the pH and speed up the reaction process. Sodium and Potassium are commonly used as alkaline activators, especially to activate ground granulated blast furnace slag (GGBFS), which is a residue from iron ore ovens.
2. F Group: This group has pozzolanic properties and is characterized by a high $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 > 70\%$ content. The pozzolanic reaction occurs when $\text{SiO}_2 + \text{Al}_2\text{O}_3$ reacts with the calcium hydroxide Ca(OH)_2 from the cement reaction. Most types of HFA are F group fly ashes. These types of ashes are commonly mixed in cement.

The reaction product from the cement is necessary to create the pozzolanic binding function. This pozzolanic binding consists of $x\text{CaO}\cdot y\text{SiO}_2\cdot z\text{H}_2\text{O}$ and $x\text{CaO}\cdot a\text{Al}_2\text{O}_3\cdot y\text{SiO}_2\cdot z\text{H}_2\text{O}$. (Biernacki, 2001). The base environment created by the $\text{Ca}(\text{OH})_2$ speeds up the reaction between the Calcium and the Silicon.

“Class F FAs are commonly produced from the burning of higher-rank bituminous coals and anthracites and these FAs are pozzolanic in nature (hardening when reacted with $\text{Ca}(\text{OH})_2$ and water). On the other hand, the high-calcium Class C FAs are normally produced from the burning of low-rank lignites and sub-bituminous coals and these FAs have both cementitious (self-hardening when reacted with water) and pozzolanic properties” (Vassilev and Vassileva 2007)

The chemical composition is not the only determinant for the characteristics of a binder. The mineralogical structure, which determines the way the molecules are structured, plays an important role in the functionality of a specific binder. Amorphous glasses tend to be more reactive than crystalline structures. The different glass structures all have their own characteristics. The temperature in the processes is an important factor in the creation of the glass phases. A high amorphous glass content will increase the binding function (Pacewska, Blonkowski et al. 2006). Glass particles tend to solute faster when exposed to extreme conditions. Both a high and low pH value speeds up the solution of glass particles. When the glass particles solute and the elements come into solution, they can react to form long chains of atoms, which create the binding function. Not only the chemical but also the physical characteristics play an important role in the reactivity of the fly ashes. Smaller particles are more reactive than larger ones. This is because the total surface area (contact area) is much larger with small particles than with large particles, so they will solute faster. Grinding the particles can increase their reactivity, but this process is energy-consuming. The costs and benefits of the grinding process have to be considered.

The characteristics of the LFA will determine a range of possible applications for the specific LFA will be. Apart from the “conventional” applications of fly ashes (pozzolanic and cementitious), there is a possibility to create geopolymers from fly ashes (Dombrowski, Buchwald et al. 2007).

Geopolymers are synthetic aluminosilicate materials which can create a binding function. In collaboration with the University Delft the option of using LFA as a raw material for the creation of geopolymers has been researched. This contributed to finding alternative ways of processing of LFA.

3 Research Methodology

This study consists of four major steps.

1. Literature research: in which LFA production and processing practices are being identified.
2. Field research: contacting and visiting LFA producing and processing companies in order to obtain LFA samples and get an insight in the practice.
3. Testing research: in which the chemical and physical characteristics are determined. This was done in order to review the applicability and the environmental impact.
4. Data analysis: the first step in the data analysis is determining the applicability of the LFA. This is important to make a comparison to conventional building materials. The environmental impact of the various processing options is determined by Life Cycle Analysis (LCA). This data analysis method is used to translate the emissions that are caused by processing LFA into environmental impacts.

In this chapter the way these four steps were carried out will be explained. It will give more detailed information on the type of research that was done and the methodology that was used.

3.1 Data collection

Data collection has been subdivided in three different elements: literature research, field research and testing research. The data was collected in different ways. Scientific articles were consulted to form the basic knowledge on LFA, LCA, Concrete and Geopolymers. With this information a research plan and testing strategy were developed. The cooperation of several companies, institutes and university was required to gather additional necessary information. EN standards, which are the European testing standards composed by the European Committee for Standardization, were used to ensure a uniform testing method which is used throughout Europe.

3.1.1 Literature research

Articles on LFA, LCA, Concrete and Geopolymers from the University library and the internet were collected and scanned. A large fraction of the required information was obtained from these articles and referenced sources from them. On the basis of contact details provided in some articles contacts were established with departments from the Universities of Delft (The Netherlands), Thessaloniki (Greece) and Weimar (Germany) have been established. They have provided additional detailed information and relevant literature.

Simapro 7.1 (Pre 2009) was used as tool to analyze the data but also contained a source of LCA data and background literature. The Simapro program as installed at the University of Utrecht contains several databases in which the emissions of several products are modeled. The Ecoinvent database (Ecoinvent 2009), which is available in Simapro 7.1, provides the necessary data on emissions from the production process of raw materials and production process of the modeled building materials. This is the most extensive database and was therefore primarily used in this research. For materials

or process that aren't modeled in the Ecoinvent database other available databases such as the ETH-ESU 96 were used. The records that are used in the LCA will be specified.

3.1.2 Field research

Literature review only was not sufficient for conducting the present study. Active field research was required in order to obtain essential information. By visiting both EON and RWE power plants, their lignite mines and LFA processing facilities new insights about the process were gained. In Table 1 the most important actors are described (an elaborate description can be found in the preface). The electricity companies provided LFA samples and some information about the production and processing of LFA. B|A|S, Henk Nugteren and Rob Comans provided field specific information on respectively concrete, geopolymers and leaching. These actors also assisted in developing the testing methodology. B|A|S and the Geolab provided the testing facilities that were required for concrete and leaching research.

Actor	Organization	Type of organization	Role within project	Location
B|A|S	B|A|S	Concrete research institute	Provided concrete testing faculties and supervision	Venlo, the Netherlands
Evert Nieuwlaar	University Utrecht	University	Personal supervisor	Utrecht, the Netherlands
Geolab UU	University Utrecht	Chemical research laboratory	Leaching research facility	Utrecht, the Netherlands
Henk Nugteren	University Delft	University	Assisted and facilitated the Geopolymer research	Delft, the Netherlands
Rob Comans	ECN	Energy research center	Assisted the leaching research	Petten, the Netherlands
Electricity companies	RWE, EON, ČEZ, PPC	Electricity companies	Provided LFA samples and process information	Germany, Czech republic and Greece

TABLE 1 PROJECT INVOLVED ACTORS AND THEIR FUNCTIONS WITHIN THIS STUDY

LFA collection

The task of gathering LFA samples from various regions in Europe is complex. In order to perform this research cooperation from LFA producing companies was required. Different companies and organizations were targeted. . Although there was a low response rate to e-mails and telephone calls, eventually a representative set of samples was acquired from electricity companies, universities and fly ash processing companies.

It was found that the electricity companies that produce the LFA are not always the same companies that process the LFA. In Mitteldeutschland for instance, the lignite is mined by the MIBRAG, while the electricity is produced by EON and the processing of the waste is done by the MUEG. On the contrary, in the Rheinland region the entire process is done by RWE.

Process information

Data about processes within the Lignite fired power plants proved hard to obtain. Within large companies every person has his own function and it is therefore hard to get in contact with a person that has an overview of the entire process from lignite mining to LFA disposal. Information on the LFA disposal is particularly hard to obtain. Companies are not willing to give information on processes that could cause negative publicity. According to the European Union directive environmental impact assessment 85/337/EEC “public and private projects which are likely to have significant effects on the environment should be granted only after prior assessment of the likely significant environmental effects of these projects has been carried out” (European-Union 1985). An EIA should be made on the environmental effects of LFA deposits. However, although several electricity companies, universities, EIA organizations and other parties were contacted, no EIA rapport on LFA deposits was obtained. Data on emissions from the LFA deposits had to be gathered through leaching research.

3.2 Testing Methodology

Different tests will be conducted to determine the characteristics and applicability of the LFA. These tests can be subdivided in three different categories. The LFA characteristics will be determined to get a better understanding of the chemical functioning of the LFA. LFA applicability is tested to make a comparison in the technical performance with the reference mortar. Furthermore leaching tests are going to be done to determine the emissions from LFA deposits. This section will describe the testing methods used and their relevance.

3.2.1 LFA characteristics

Grain size distribution: Laser-diffraction can determine the particle sizes within a powder. The spread of the particle size is an important factor in reactivity and function within the mortar. Smaller particles have a higher specific area and will solute and react much faster than a larger particle. The buildup of the grain sizes is also important for the packing effect. A homogeneous spread in size with little peaks will perform better in a mortar.

- Laser-diffraction devices can calculate the grain size distribution within the powder. The device that will be used is the Rodos R4 (Sympatec 2009) that can measure from 1.8 μ m until 350 μ m, this is a standard range for cement and fly ashes.

Chemical Compostion: XRF analysis can determine the chemical composition of a substance. The chemical composition is relevant to get more understanding of the material. It can give an indication of the reactions that will occur and the reaction products that are created.

- The specific machine that will be used can measure all inorganic materials. From the element Sodium (Na11) until Uranium (U238)

Based on the outcome of the characteristic analysis the strategy for application testing is to be determined. The most promising 5 LFA samples that represent a large production will be tested for applicability.

3.2.2 LFA applicability

The most important factors for applicability of LFA in concrete are processability and strength. These factors will be tested by creating different mortars according to the EN 196 standard. To assess the performance of a hydraulic binder, a mortar that consists of sand, water and hydraulic binder will be made. The goal of the tests is to assess the performance of the different hydraulic binders. These hydraulic binders consist of cement, or a cement LFA combination. In the EN 197-1 all the different types of cement are described. The LFA CEM I mix could be defined as a new type of composite cement. In this study both LFA and CEM I are perceived as ingredients of mortar or concrete. This is done because there are specific requirements on the composition in the EN 197-1. It is a complicated procedure to certify new composite cement. Furthermore, the exact recipe of the concrete mixture can be adjusted to the exact need of the application. A third reason not to include the LFA in composite cement is the extra transport that is needed. If LFA would be mixed in composite cement it would have to be transported to the cement factory, before the total composite is transported to the concrete factory. If used as a concrete ingredient, it can be directly transported to the concrete factory.

Because a difference analysis is done and aggregates like gravel have no binding function there is no need to include them if they remain the same in all concrete recipes. The cement in the mortars will be replaced (on the basis of weight) with different percentages of LFA. Three categories will be tested: 15%, 30% and 45%. These categories are chosen because 30% is mentioned as an optimum of cement replacement in several sources (Dietz and Ma 2000; Koukouzas, Vassilatos et al. 2005). In total three categories were chosen to limit the amount of work. The value between 0% and 30% is 15% so this was chosen as the first category. The same difference was added to the 30% to see what the influence of higher LFA concentrations would be (45%). Processability is determined by the consistency of the mortar.

Consistency has to be researched to determine the processability of the mortar/paste. If this mix is too thick it will not be easy to process. The water proportion of the mixture can be altered until the correct consistency is reached.

- The consistency of a mortar is determined by the flow of a mortar. This is tested by lifting a flow cone with mortar (directly after mixing) and dropping the glass plate on which mortar stands 15 times according to the EN 1015-3 standard. Every time the plate drops, the little shock causes the mortar to spread. After this procedure the diameter of the spread is measured.

This will be done with all of the mortars. These mortars will be made with a standard water/powder ratio of 0.5 as described in EN 196/1.

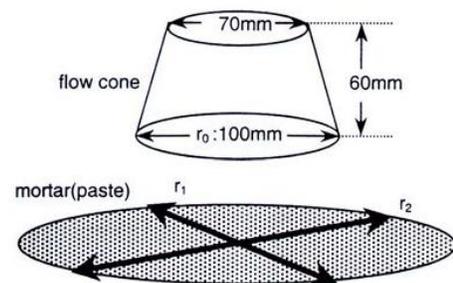


FIGURE 5 SPREAD DETERMINATION TEST ACCORDING TO EN 1015-3

The mortar that has the largest spread difference in comparison to the reference mortar will be reconstructed with an adapted amount of water. The water requirement will be

adjusted until the reference spread is reached. This is done to determine the influence of the water concentration. This category will be called adapted water (AW).

To determine the water requirement of the AW mortars, the spread of the cement paste is compared with the spread of the LFA paste. A paste is a mortar without sand (only water and powder). This spread test is done in accordance with the KIWA 73/06 criteria and resembles the EN 1015-3 test. The same flow cone is filled with paste (Figure 5). Only the glass plate doesn't have to be dropped. When the flow cone is lifted the paste spreads naturally. This spread is measured.

Strength tests are necessary to compare the actual strength of the LFA-cement to a cement binder. Flexural strength tests are not as important as compressive strength test, because the tensile strength in the concrete is normally controlled with steel reinforcement.

- Flexural and compressive strength tests are conducted according to the EN 196-1 standard. This is a European standard for testing the strength of cement. This standard can also be used to compare other binders like LFA. Mortarprisms from each category are made. These



FIGURE 6 THREE POINT FLEXURAL STRENGTH TEST, RESULT AND COMPRESSIVE TEST ACCORDING TO EN 196-1 are small beams from 40mm x 40mm x 160mm. To ensure reliable results three prisms from each category will be constructed. From every prism 1 flexural strength test and two compressive strength tests can be done. This means that for each category 3 flexural measurements and 6 compressive measurements will be done. This is done after two periods of time: 28 days and 90 days. The 28 days is a standard time used in almost every concrete strength research. The 90 day test is done to determine the pozzolanic activity which requires more time. The cement prisms are created as a reference.

LFA Region	Replaced cement 15%	Replaced cement 30%	Replaced cement 45%	Replaced cement 30% AW
LFA 1				
LFA 2				
LFA 3				
LFA 4				
LFA 5				
CEM 1 42,5R ENCI				

TABLE 2 TESTED LFA/CEMENT PRISMS, FOR PROCESSABILITY AND STRENGTH (GREY INDICATES TESTED CATEGORIES)

For the strength research a total of 19 categories have been constructed. This means that 19 categories x 3 prisms per categories x 2 periods = 114 mortarprisms have to be made and tested.

3.2.3 Leaching

To know what the effects of depositing LFA in the reference scenario is, the leaching behavior of the LFA was researched. The emissions of various substances to groundwater will have to be modeled. There are different types of tests to determine the leaching behavior of LFA. A short description of the common leaching tests is given below:

Shake test: The Shake test is a relatively simple test to determine the solubility of different substances from a fly ash. The LFA is mixed with water and shaken for a predetermined period (48h). After the shaking period the water is filtered so that the leachate can be measured on ICP-OES for main components and on ICP-MS for trace components. There are two main variations within the shake test.

1. L/S dependable shake test: The L/S (liquid/solid) can be mixed in different ratios. This is done to determine the saturation level. LFA. L/S 2 is used to simulate a situation where time is limited. L/S 10 is used to simulate a longer period of leaching. The results of the L/S 2 and L/S 10 test can be compared to see if the leaching will continue or if the substances are solved instantly.
2. pH dependable shake test: The pH is a factor in the solubility of various substances such as heavy metals. This is why the shake test is executed at different pH-values. This test is done to get an indication about the maximum leachability of the different LFA's. For most substances a low pH-values stimulate the solubility. The pH dependable shake test is executed at three pH-levels, pH V, N and X.
 - a. pH V: represents the shake test at the natural pH of the LFA.
 - b. pH N: represents the shake test at neutral pH (pH7). During the test basic or acid fluid is added to keep the pH at this level
 - c. pH X: represents the shake test at an extreme pH. For basic LFAs this means pH4, for acidic LFAs this means pH12. During the test basic or acid fluid is added to keep the pH at this level.

Column test: The column test is a more realistic simulation to the leaching behavior of LFA deposits. These tests are relatively more extensive than shake tests but give a more realistic image of the percolation in a deposit.

pH-stat test: The pH-stat test can be done to determine the buffering capacity of the LFA. Most LFA's have a high pH-value (above 12). There can be a difference in the buffering from LFA's with a pH of 12. If the pH needs to be lowered to 7 or 4, the acid demand can vary between different fly ashes. With the pH-stat test, the pH of the water (with fly ash) is kept constant. On predetermined time intervals the pH will be measured and acid or bases fluids will be added to correct towards the accurate pH. This test can be done to determine the amount of OH⁻ or H⁺ that is released to the

water. Large amounts can change the pH of the water which in turn has effects on the environment. The pH also has an influence on the solvability of the substances.

In this research the four different shake tests were executed. Two tests with different L/S ratios, L/S 10 and L/S 2, and two tests at different pH levels. Because of time and finance shortages it was not possible to execute the column and pH-test. These tests would have given a more realistic image of the actual leaching. The shake tests however do give an indication of the substances that will be leached in the environment. It would be interesting to execute column and pH-stat tests in further research.

3.3 LFA Applicability

After specific data has been composed by executing the tests described in §3.2, the results can be analyzed. To compare the different processing options subsequent steps have been taken. The mortars that are produced with LFA have to be comparable with conventional mortar. The applicability is assessed on the basis of several factors. These main factors are processability and strength. Other factors like heat of hydration, shrinkage, set time, creep, modulus of elasticity, and soundness are also informative but are considered of secondary importance and therefore will not be assessed in this research. The assessment of strength and processability are done on the basis of results of tests described in § 3.2.2.

The material specifications of the tested materials have to be within the same strength class as the reference material to be considered of same applicability. Within the EN 196-1 standard a method is provided to determine the performance of a hydraulic binder. The EN 197-1 standard can be used to categorize the results of the EN 196-1 standard. Three main strength classes are defined in the EN 197-1 standard Table 3).

Cement Strength class	Strength standard MPa (28 days)	
32,5	≥32,5	≥52,5
42,5	≥42,5	≥62,5
52,5	≥52,5	-

TABLE 3 EN 197-1 COMPRESSIVE STRENGTH CEMENT CLASSES

A clear distinction must be made between normal (N) and rapid (R) hydraulic binders. This applies to the 2 days strength which can be important for the moment of demoulding. The 2 days strength will not be tested in this research. Normal reference cement 42,5N will be used construct the reference and LFA mortar. The results of the EN 196-1 tests are going to be used to determine if the hydraulic binder (LFA + cement) meets the requirement of the 42.5N cement according to the EN 197-1 standard. Normally the standard requires a large set of tests to certify a cement for a specific class, but in this case only six compressive strength measurements are done per type of hydraulic binder. Based on these tests an indication on binder performance can be obtained. The average value of the six tests will be used to assess compressive strength. If one of these measurements deviates more than ±10% of the average, they will not be considered.

In practice the constructor specifies the requirements of the concrete that needs to be used according to the EN 206-1 (Table 4). In this standard the strength requirement of concrete are defined. The different strength classes are defined more accurately than the strength classes of cement. The EN 206-1 standard differentiates between strength tests with cylinders and cubes,

because of the different testing methods used throughout Europe. If the LFA will be applied in concrete structures, this LFA-concrete needs to be tested according to EN 206-1. The testing of actual concrete, with large aggregates, is however beyond the scope of this research.

The aggregates that are used can play an important role in the characteristics of the concrete. Because only the performance of the hydraulic binder, the EN 197-1 strength classes are going to be used to assess the strength.

Processability of the LFA in concrete is based on the consistency of the mortar. Consistency can be tested through the flow of the mortar EN 1015-3 standard. The tested material was considered to have the same applicability as the reference material, if the flow

remained within $\pm 10\%$ of the reference mortar. If the flow isn't within this range, the W/P factor will have to be adapted. This doesn't mean that the materials that were not within this range were not applicable, only that it cannot be applied in the same way as the reference material. For applications of which the requirements are lower than the results of the reference material the LFA could still be applied.

Concrete strength class	Cylinder MPa	Cube MPa
C12/15	≥ 12	≥ 15
C20/25	≥ 20	≥ 25
C28/35	≥ 28	≥ 35
C35/45	≥ 35	≥ 45
C45/55	≥ 45	≥ 55
C53/65	≥ 53	≥ 65
C60/75	≥ 60	≥ 75
C70/85	≥ 70	≥ 85
C80/95	≥ 80	≥ 95
C90/105	≥ 90	≥ 105
C100/115	≥ 100	≥ 115

TABLE 4 EN 206-1 COMPRESSIVE STRENGTH CONCRETE CLASSES

3.4 Life cycle assessment (LCA)

LCA is a method to determine the environmental impact of a product. It can be used to analyze the impacts from the stage of initial production of raw materials to the product, through its the production and use stages of the product itself, to a stage of its disposal - in other words from “cradle” to “grave”. In order to conduct an LCA, the environmental interventions in all production processes that are required to produce a product, have to be taken into account. These environmental interventions consist of several types of emissions and use of resources. The system boundaries have to be determined to restrict the research to its goals. The choices that are made in this specific LCA are presented in this section.

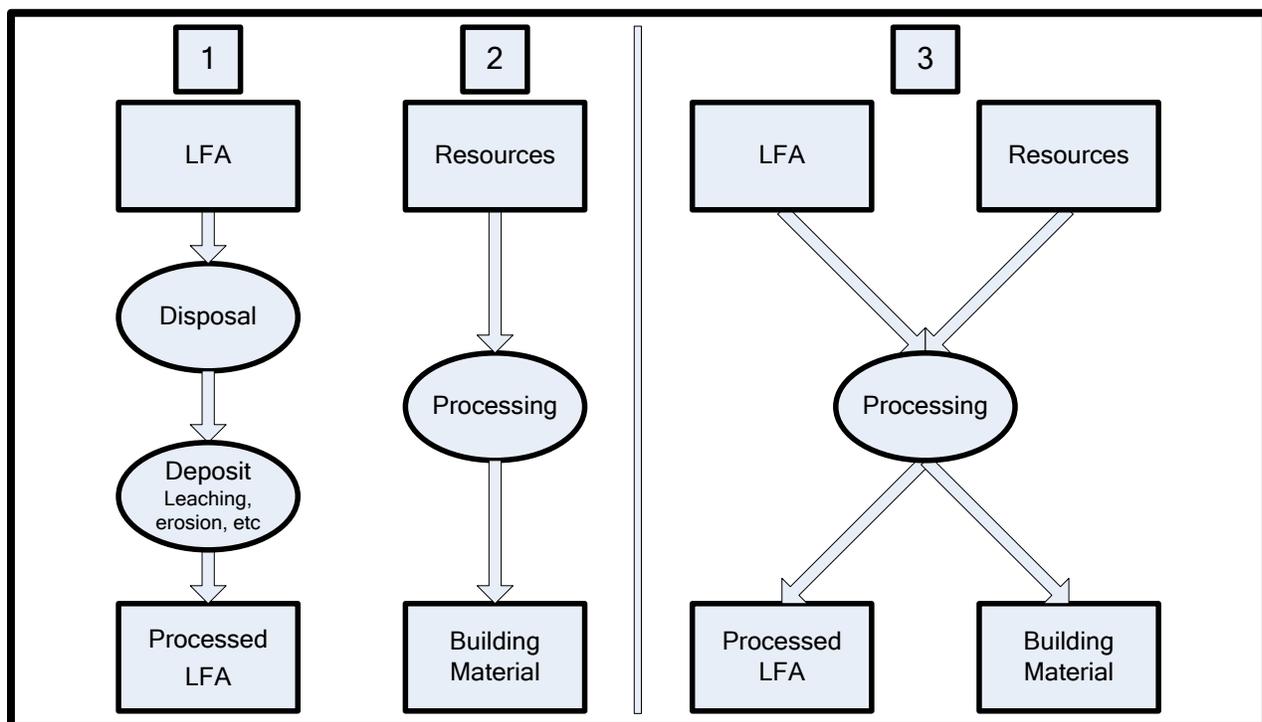


FIGURE 7 SIMPLIFIED FLOW CHART OF THE DIFFERENT OPTIONS TO PROCESS LFA

This LCA uses three scenarios to compare the LFA processing options (Figure 7). Scenario [3] describes a system in which LFA is processed in the building industry. This system fulfills two functions: processing LFA and constructing building material. To cope with this multi-functionality problem this LCA consists of two reference scenarios. The scenario in which LFA is deposited in a depleted lignite mine [1] and the scenario of conventional production of building materials [2]. Those scenarios combined are actually one scenario which describes the current situation of processing LFA and producing building materials.

The building materials of scenario [2] & [3] should have the same application possibilities. When there are different building materials that are researched both scenario [2] & [3] have to be reconstructed. The different methods of depositing in various regions will lead to the creation of multiple depositing [1] scenarios.

The LCA of geopolymers is a specific scenario that resembles scenario [3]. Because the recipe and testing procedures deviates from those of conventional and LFA-concrete a difference analysis is not possible. Therefore, it is not considered as a separate scenario in the present LCA. Furthermore the tests that will be done with geopolymers are only done to form an indication on the possibilities. The environmental impacts concerning the production of geopolymers and the methodological choices made to execute the research will be discussed in §7.3.

In order to ensure that the LCA procedure is comparable in different countries international LCA standards have been developed by the International Organization for Standardization (ISO). The ISO 14040:2006 (ISO 2006) describes the principles and framework for LCA.

The intended application of the LCA results is considered during definition of the goal and scope, but the application itself is outside the scope of this ISO standard. The LCA process consists of 4 main steps (Baumann and Tillman 2004):

1. Goal and Scope Definition: The goal and scope definition is done in order to define the framework in which the LCA is conducted. When this framework is completed a functional unit has to be described within a defined set of boundaries.
2. Inventory Analysis (or Life Cycle Inventory, LCI): In which the different environmental interventions are identified and quantified.
3. Impact Assessment (LCIA): After LCI has been done the environmental interventions are classified in the different impact categories. Subsequently the environmental interventions in each category are characterized with the corresponding characterization factors.
4. Interpretation: The eventual results of the impact assessment have to be interpreted to draw conclusions. Critically reviewing of the results, methods and limitations of the LCA, is important in the interpretation phase.

In the following section a short overview on the content of the different steps is given.

3.4.1 Goal and scope

Goal

The goal of this research is to determine the potential environmental benefits of using LFA to partly replace cement in a concrete mixture.

Lignite electricity companies (*LFA producers*), building material producers (*LFA users*) and environmental policy makers (*LFA regulators*) can use this research results in their decision making processes. The final report will provide indirect policy recommendations for these three parties.

Scope

The scope of this research is LFA production and processing within the EU-27. There are two reasons to restrict the research to the EU; first, due to availability of information. Within Europe there is relatively good data on LFA processing and production of building materials. There are

different methods of LFA processing in the European countries. Investigating the different impacts of these methods will provide useful information in the decision making process. Secondly, Europe is chosen as the research area because of the ever increasing environmental regulation from the EU. The EU has the capacity to construct a guideline on the processing of LFA. A uniform European policy can be constructed.

Functional unit (FU)

The functional unit is that will be used in this research is **1 tonne processed LFA**.

There are different ways to process the LFA. The reference scenario is dumping of the LFA [1].

There are two processes in this scenario. First, the actual disposal of LFA from the power plant into the LFA deposit. This also involves the preparation and possible sealing construction of the LFA deposit. Secondly, the processes within the LFA deposit have to be considered. When LFA is stored there can be interactions between the dump and the environment. Erosion, emissions and leaching are processes that can occur on the LFA deposit.

Another way to process LFA is to use it in the production of building materials. This is described in scenario [3]. This scenario fulfills two functions: processing of LFA and the production of new building materials. The aim is to process the LFA in a building material such that there is minimal exchange of polluting substances from the LFA and the environment.

The second function is the construction of building material. This building material could replace conventional building materials. The environmental impact of the conventional building materials that are replaced is determined in scenario [2].

The amount of building material that is produced simultaneously with 1 FU has to be determined in scenario [3]. The amount of building material (weight) is the FU for scenario [2]. This functional unit will further be described as FU [2]. If for instance 3 tonne of concrete would be the FU [2], the characteristics of this concrete have to be described. There are many different types of concrete which have different strength, drying time, permeability and other specifications. These specifications are described in the EU BS 8500 concrete standards (Harrison 2003).

The environmental impacts of the various scenarios have to be calculated. Finally, to determine the environmental benefits of 1 FU, the impact of scenario [1] and [2] have to be subtracted from the impact of scenario [3]. $\text{Benefits} = ([1] + [2]) - [3]$.

This functional unit is useful from a LFA producer's perspective. In order to determine the environmentally best option for processing LFA, the environmental impact of 1 tonne processed LFA has to be determined. The producer of LFA is however not the only actor that determines in which way LFA will be processed. In order to assess the potential of processing LFA in concrete we have to take the demand into consideration as well. When a concrete consumer assesses the concrete based on the environmental performance, the second FU **1 m³ concrete** is relevant. This is why a comparison based on the environmental performance of 1 m³ of the different types of concrete will also be made. In this way the environmental performance of conventional concrete, LFA-concrete and Geopolymer-concrete can be compared. When LFA is used in the concrete, the emissions of dumping have been prevented. These prevented emissions are allocated towards the environmental profile of the concrete because the concrete actually processes the LFA.

System Boundaries

To compare the various scenarios it's important to determine the system boundaries. In a conventional LCA all the emissions from cradle to grave have to be considered. Because this LCA is a difference analysis only the differences between scenario ([1] + [2]) and scenario [3] have to be modeled. This means that not all processes are included in this LCA and that it will not give a complete LCA result about the separate scenarios. Because the depositing is not necessary in scenario [3] the complete depositing scenario has to be modeled. Only the differences in producing conventional concrete and LFA-concrete have to be modeled. The system boundaries of both concrete production and dumping options are shown in (Figure 8).

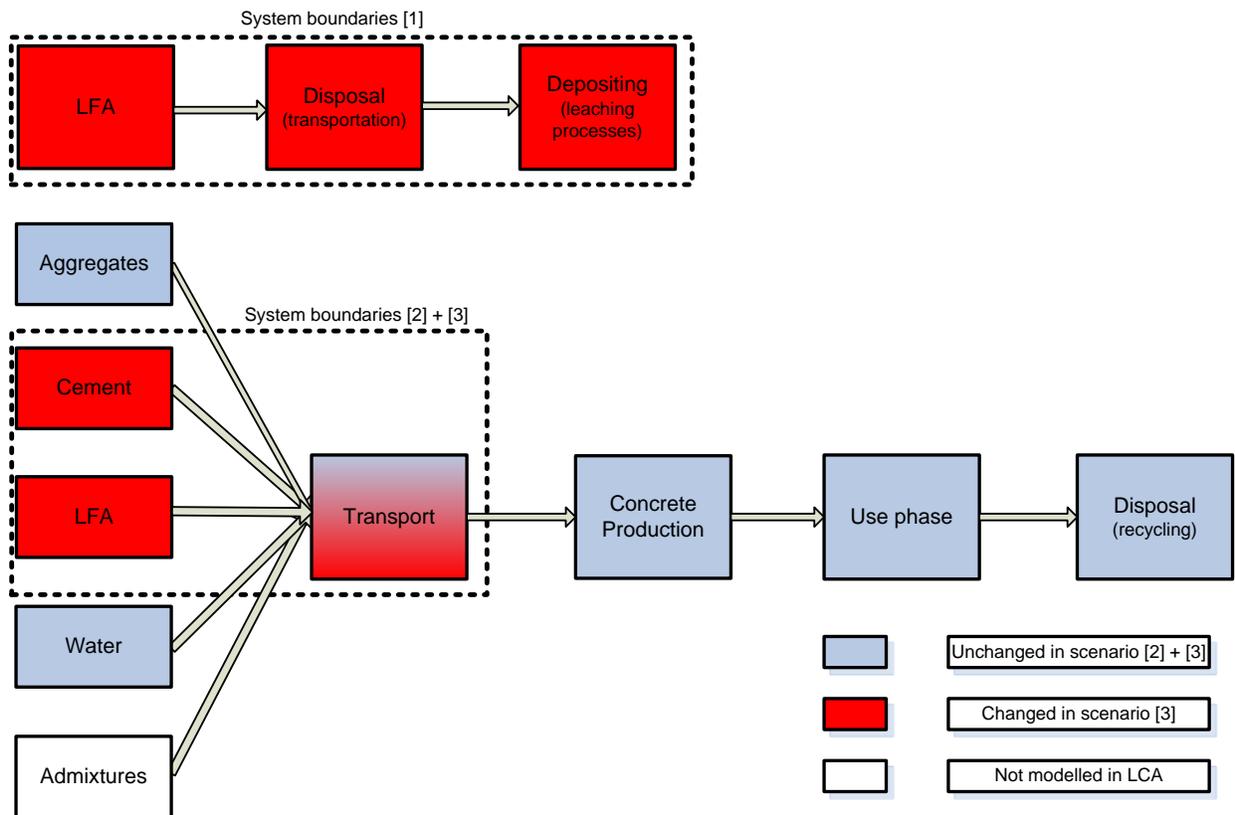


FIGURE 8 PRODUCTION LIFE CYCLE AND SYSTEM BOUNDARIES

Additionally, as Figure 8 shows, not all materials and processes are modeled in this LCA. The various resources are transported to the processing location where they are mixed into concrete. After that, the concrete is used during its lifetime. Finally the concrete is demolished and processed. The differences between conventional concrete [2] and LFA-concrete [3] is indicated with colors. The blue color indicates the resources and processes that are identical for both conventional and LFA-concrete. The red color indicates the resources and processes that differ in both scenarios. The white color indicates the resources and processes that will not be used and modeled in the LCA. It is assumed the use of aggregates will not change by adding LFA in the concrete recipe. Although it is known that the water requirement can change slightly by adding LFA to the recipe this effect is not considered significant. Furthermore the environmental impacts of water use are relatively insignificant; the differences therefore will have little effects on the environmental impact.

Admixtures like retarders and plasticizers are normally used in concrete mixtures to control binding speed and consistency. Because they are not added in the tested mixtures they were not modeled in this LCA.

Impacts of transport will also change when the resources that are transported are changed. The transport system itself will change according to the resources that will be used in the concrete. LFA can be processed in the same way as cement and is added to the concrete mixture by simply removing necessary portion of cement mass and replacing it with LFA. Therefore, the production process (mixing) of LFA-concrete is the same as that of a conventional concrete. No changes to machine equipment or processes are needed to construct LFA-concrete. The same recipe can be used, implying same aggregates for traditional and LFA-concrete. In the use phase of the concrete, weathering can also cause leaching. Leaching limits for building materials are defined in regulation. In the Netherlands these leaching limits are described in Buildings Materials Decree, other European countries have similar regulations. At KEMA in the Netherlands, research was done on the leaching behavior of several building materials (Meij, Kokmeijer et al. 2001). The research also included conventional concrete and concrete with 20% HFA. No significant changes in the leaching behavior between the two types of concrete were found. Furthermore all the values were well within the prescribed limits. In a concrete construction most substances are very well immobilized and will not leach. The elements are incorporated in amorphous molecular structures that will not dissolve in the high pH environment within the concrete (Macphee, Taylor et al. 1993). It is assumed that LFA will have the same leaching behavior in concrete as HFA. Because this LCA is a difference analysis, the use phase will not be modeled.

The building material however also has a specific lifetime and has to be processed at the end. The building materials from scenario [2] + [3] should have the same characteristics and performance. Recycling and disposal of the concretes is not considered, because it is assumed that they would be recycled and disposed in the same way (Babbitt and Lindner 2008 (1)). It is assumed that the material will be recycled, the old concrete will granulated and used as aggregate in new concrete. This recycling of concrete as an aggregate for new concrete is a new process that is currently being developed (González-Fonteboa and Martínez-Abella 2007). When currently produced concrete enters the end-life cycle, it is assumed that concrete recycling will have become common practice. Therefore the “cut off” of the life-cycle is made before the disposal phase.

Within the recycling process the granulating of the concrete will cost some energy, but this process is the same as with conventional concrete. This way the material directly enters a new lifetime and doesn't have to be disposed. When the product enters another life-cycle it is “cut off” from the previous life-cycle. The energy which is required to granulate the concrete is allocated to the life cycle of the new concrete.

The exact time of grave is hard to determine. In LCA, the impacts of “processing of LFA” have to be determined throughout the entire lifetime of the product. The product in this case is processed LFA, but it has to be determined when the LFA is processed. It is assumed that the LFA is processed as soon as it is incorporated in the concrete.

The depositing of the LFA poses the same problem. When is the LFA processed? “For a mineral waste landfill containing fly ashes from incineration, leaching may continue for thousands of years until it reaches a tolerably low level” (Astrup, Mosbæk et al. 2006). There are no leaching data on such a time scale. The best data on landfill leaching will be on a timescale of a few decades. Based on

this data estimates can be made about future leaching behavior. The estimates become increasingly uncertain looking further into the future (Damgaard, Simone Manfredi et al. 2007). In this LCA a time horizon of 100 years is chosen. After this period most of harmful trace elements will be leached out or remain in the dumpsite. The LFA is considered processed after this period.

3.4.2 Inventory Analysis

The inventory section consists of a detailed description of the inputs and outputs of the various scenarios. The inputs are made up of raw materials and fuels into the concrete production and dump process. The outputs consist of solid, liquid and gaseous emissions from the systems. For every type of LFA researched an LCA inventory will be done. If there are different possibilities to process the LFA into a viable applications different LCA's have to be constructed. For every different region scenario [1] has to be reconstructed. If the applicability of the LFA changes scenario [2] + [3] have to be reconstructed as well. Most of the inventory results consist of specific emissions which are not directly relevant for the reader. This is why only remarkable results will be presented.

Allocation

The materials, emissions and energy used in a production process have to be allocated to the products produced in that production process. It is assumed that LFA is a waste product of lignite-fired power plants and that no environmental impacts of the production in these power plants are allocated towards the production of LFA. The environmental impacts that occur during the burning of lignite (the production process of LFA) are allocated to the electricity that is produced. This can be done if economic allocation is applied. Because LFA is generally considered as a waste product with no economical value. All the value in the production is generated by the electricity. Because the scenario [3] (using LFA in the building industry) fulfills two functions, a multi-functionality problem occurs. The correct way to solve the multi-functionality problem is system expansion (ISO 14040). Because scenario [3] fulfills an extra function in comparison with scenario [1], scenario [2] is added. Together scenario [1] + [2] fulfill the same function as scenario [3]. If in the future the demand for LFA would increase and a price would be established the situation would change. The allocation could then be done on the basis of price. If the demand and price of LFA increases, the emissions produced with the burning of lignite will have to be allocated to LFA as well. In this same way the emissions of the GGBFS are calculated. This will be addressed in §7.3.

3.4.3 Impact Assessment

The impact assessment is done to evaluate the magnitude and significance of the environmental impact. With the impact assessment, a comparison between the product systems can be made to get a feeling for the relative impact. There are several environmental impacts categories which have different sources and effects. The CML 2 baseline 2000 scenario (CML 2001) is the dataset used to characterize the emissions of the flows determined in the inventory analyses.

The emissions can be categorized in impact categories. Because emissions have a different impact in a category, the emissions have to be calculated to equivalents. Based on the ISO 14040:2006,

CML constructed a comprehensive set characterization factors that characterize the most important emissions in the relevant impact categories. These were incorporated in the CML 2 baseline scenario. The CML 2 baseline can be selected in Simapro 7.1 (LCA software), its impact categories are presented in Table 5.

Impact Category	Unit
Abiotic depletion	kg Sb eq
Acidification	kg SO ₂ eq
Eutrophication	kg PO ₄ eq
Climate change	kg CO ₂ eq
Ozone layer depletion	kg CFC-11 eq
Human toxicity	kg 1,4-DB eq
Fresh water aquatic ecotoxicity	kg 1,4-DB eq
Marine aquatic ecotoxicity	kg 1,4-DB eq
Terrestrial ecotoxicity	kg 1,4-DB eq
Photochemical oxidant formation	kg C ₂ H ₄

TABLE 5 ENVIRONMENTAL IMPACT CATEGORIES CML 2 BASELINE

After characterization has been done and emissions in each impact category are determined it can be valuable to compare the results of the different categories. This means that each impact category is divided by the reference. When normalization is used, the average yearly environmental load in a specific area, divided by the number of inhabitants, is used as the reference. With normalization in the CML 2, the scores of all impact categories can be divided by the average emissions of a European citizen. In this way a relative comparison of the different impact categories can be made. It can give an indication on the significance of the contribution in each impact category. Therefore the characterized results of the environmental impacts of 1FU will be normalized.

3.4.4 Interpretation

Interpretation of the results is an important element of LCA. It has to be done throughout the entire LCA process. The results have to be placed in the context of the goal of research. The LCA results are expressed in the characterized equivalents of each impact category (Table 5). These values represent the environmental impact of the different processing options. Environmental impacts of the different components in the processing options will be compared. The impacts of for instance the transportation of LFA will be compared with the impacts of cement production. In this way it can be seen which processes make the largest contribution in each processing option. The impacts of processing the different LFAs will be compared in order to assess the variation between the different LFAs.

The conclusions that can be based on the normalized results are limited. This is because the impacts are relative to impacts of European citizens and not to the extent of environmental problem (the consequences of the emissions are more important than the relative amounts). Furthermore some emissions that are characterized in the CML baseline were not included in the normalization scores. This can result into too high normalized scores in some categories (Koorneef, Keulen et al. 2008).

It is hard to draw a clear end-conclusion on the characterized or normalized results. This is however not the goal of this research. The environmental impact of all processing options are presented and compared. There are too many uncertainties, LFAs and impact categories to draw one single conclusion. This study must take all factors and uncertainties in consideration in order to form a picture about the environmental impact of the different processing option.

In order to show what the effects of processing LFA in concrete are, the environmental impact of LFA-concrete is compared with the impact of conventional concrete. This will be presented in chapter 8. Finally, in chapter 9 the potential of processing LFA in concrete is assessed. The environmental performance is one of the factors which influences this potential. Based on the results of the LCA the environmental performance will be assessed.

The data and methods used to obtain the inventory results will be critically assessed. Furthermore the characterization methods in the CML 2 baseline will also be evaluated. The results of the LCA can only be interpreted correctly, if the flaws and uncertainties in the data and methods are known.

4 LFA characteristics

4.1 LFA locations

In this research different types of LFA are going to be investigated. In every region there are variations in the composition of the lignite. Firing practices and filtering methods may vary as well, which makes it that the characteristics of the LFA can change significantly.

To get an overview of LFA production in Europe, a selection of representative regions has been made. Important regions with their own specific lignite characteristics, firing practices and LFA processing methods were chosen to get a representative picture of the European situation. Contacts with electricity companies that own lignite power plants have been established in order to obtain the necessary LFA samples. In this way a representative LFA sample from different regions throughout Europe could be obtained. Efforts have been made to obtain a set of LFA samples that is representative for the European situation. The effort was focused towards the main lignite producing countries, which are Germany with 39%, Greece with 15%, Poland with 15% and the Czech-Republic with 11% of the annual European lignite production (Ecoinvent 2007). Unfortunately LFA samples from Poland have not been obtained. The locations of the different types of LFA samples that have been obtained are presented in Figure 9. Of these samples the first 10 were used as representative the LFA samples. The other samples (*italic*) served other purposes in this research and will be addressed later in §4.3.

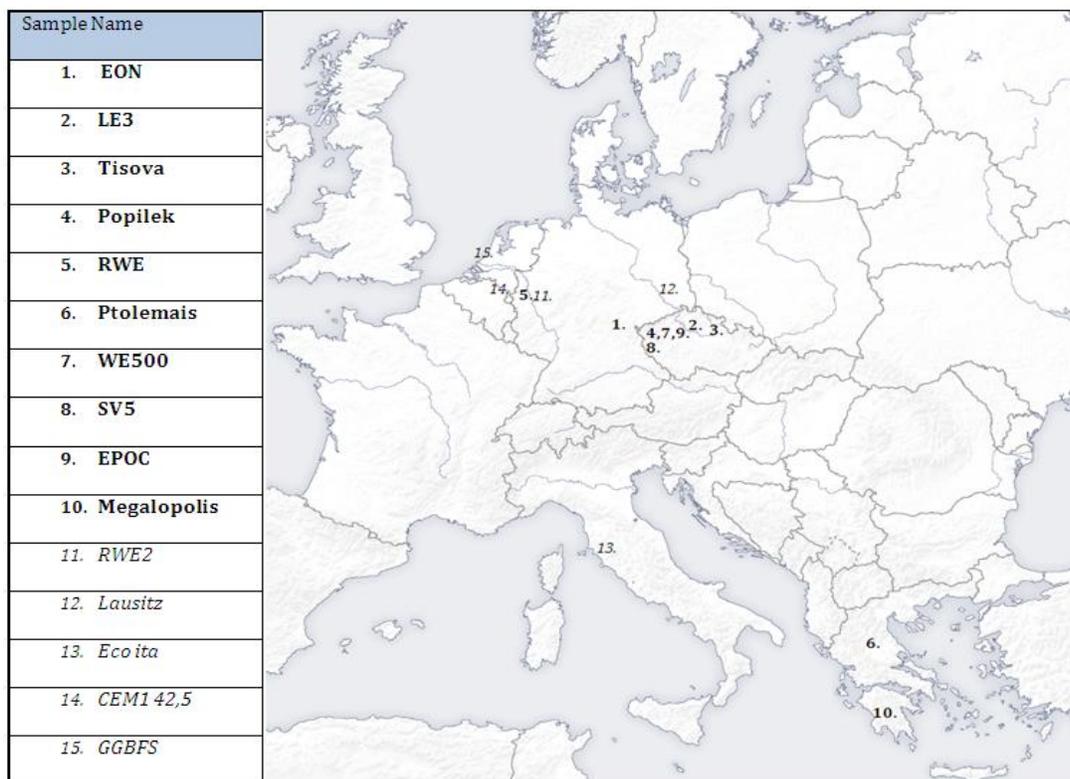


FIGURE 9 PRODUCTION LOCATION OF THE USED LFA SAMPLES AND OTHER USED SAMPLES (*ITALIC*)

4.2 LFA production and processing

The suppliers of LFA samples were asked to provide data on the production of LFA and the way it was processed. This was done to obtain an insight in the differences of production and processing methods throughout Europe. With this information the differences in LFA characteristic can be traced back. The specific characteristics of the production and processing will be discussed below.

LFA Sample	Origin	Ash content dry mass lignite %	Firing Method	FA / BA Ratio	Annual LFA production Kilo tonne	Disposal method	Leaching prevention
EON	Germany	25	Granular boiler	Unknown	Unknown	Train	Pre-reaction open pit
LE3	Czech Republic	23-30	Granular boiler	85 / 15	120 kt	Pipeline with Desulfurization water	No
Tisova	Czech Republic	35	Fluidized bed	60 / 40	170 kt	Conveyor belt sprinkling on belt	Unknown
Popilek	Czech Republic	40	Granular boiler	80 / 20	Unknown	Conveyor belt sprinkling on belt	No
RWE	Germany	Unknown	Paper ash	Unknown	8600 kt (total RWE)	Trucks	No
Ptolemais	Greece	33-40	Granular boiler	97 / 3	1000 kt	Conveyor belt sprinkling on belt	No, study in progress
WE500	Czech Republic	40	Granular boiler	80 / 20	450 kt	Wet open pit	Unknown
SV5	Czech Republic	23-30	Granular boiler	90 / 10	140 kt	Pipeline with Desulfurization water	Unknown
EPOC	Czech Republic	40	Granular boiler	80 / 20	1300 kt	Wet open pit	Unknown
Megalopolis	Greece	40	Granular boiler	90 / 10	700 kt	Conveyor belt sprinkling on belt	No, study in progress
RWE2	Germany	3	Granular boiler	Unknown	8600 kt (total RWE)	Trucks	No

TABLE 6 PRODUCTION AND PROCESSING DATA DERIVED FROM LFA PRODUCERS

Ash content: It is remarkable that the RWE2 lignite only has an ash content of 3%. The ash content of other types of lignite is roughly in the range of 20% - 40%. The supplier of RWE2 was asked to explain this difference. Up to this moment no answer was provided. It is assumed that the 3% ash content doesn't represent the realistic number.

Firing Method: Almost all types of LFA were produced using granular boilers. This is the conventional firing method that was also described in § 2.1.1 (Figure 2). Only Tisova was produced in a fluidized bed. In this type of boiler the Lignite doesn't have to be as fine as in a granular boiler. Therefore it's easier to co-fire other materials. Most fluidized bed plants also fire biomass. Because this research focuses on LFA, contaminated fly ashes were not researched. This is also why there is

only 1 type of LFA that has this firing method. Tisova was, like all other LFA samples, produced only with lignite.

Fly ash / Bottom ash Ratio (FA/BA): The finer lignite is milled, the higher the FA percentage will be. Because the Tisova LFA was produced using a fluidized bed the lignite was less fine than the other types of LFA. Fine milling does require energy, but due to a more efficient burning process, the total energy efficiency increases.

Annual production: Because the LFA samples represent a specific lignite plant, the annual production is relatively low in relation to the assumed annual European LFA production of 40 million tonne. The production of RWE is not specified for a single plant, but for the entire Rheinland area. This area alone produces about 20% of the European LFA.

Disposal method: The type of transport that is chosen to dispose the LFA also contributes to the environmental impact of the dumping scenario. Each different type of transport has another environmental profile. This will be discussed in §6.1.1. The different transportation methods also have an effect on the way the LFA reaches the deposit. Especially the amount of water that is added can have effects on the leaching behavior of the LFA. The distance between the power plant and the deposit will also play a crucial role in selecting the transportation option. No details about transport distances have been obtained. Assumption on these distances will be based on the characteristics of the transport means.

Leaching prevention: All the LFA producing and processing companies were asked which measures were taken to prevent the leaching of the LFA. It was found that only the EON presented information on leaching prevention. The LFA of EON is pretreated before it is deposited. This is done in such a way that the LFA hardens instantly and concrete-like structure, that immobilizes the elements, is formed. RWE claimed that there was a natural clay layer below the LFA deposit and that no prevention measures were needed. The other companies couldn't provide information on prevention measures.

4.3 Chemical and physical LFA characteristics

The chemical and physical characterization of the different types of LFA has been researched as described in §3.2. This has been done in order to compare their characteristics and to get an overview of the variation between the different LFAs. With this information, the causal relation between composition and function can be analysed. There are however, so many different characteristics, that a causal relation between a single characteristic and its function are hard to find based on the results found. What can be done is making the assumption that different types of LFA with comparable characteristics will have a comparable function.

In this way, the characteristics of LFA could give an indication on the function. Furthermore, this information could provide useful for further research.

Name	EON	LE3	Tisova	Popi- lek	RWE	Ptole- Mais	WE 500	SV5	EPOC	Mega- lopolis	RWE 2	Lau- sitz	HFA Italy	CEM 1 42,5	GGB FS
Nummer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO2	29,8	47,7	35,2	50,2	3,1	23,3	47,1	41,7	48,6	41,4	26,9	54,6	51,1	20,3	35,6
Al2O3	15,8	31,2	25,2	29,2	3,0	12,2	25,5	29,1	28,7	16,9	16,7	12,3	20,7	5,1	12,9
Fe2O3	5,7	4,4	7,3	5,9	9,1	6,2	4,8	9,9	5,2	8,4	6,8	7,0	7,3	3,2	0,7
CaO	31,0	0,8	17,3	1,7	41,7	30,8	11,6	3,1	2,2	14,4	23,2	8,6	3,7	63,4	40,7
SO3	8,1	0,2	6,2	0,3	19,0	10,3	3,3	0,7	0,3	4,5	10,2	1,6	0,8	2,6	1,6
TiO2	0,9	3,2	4,8	2,0	0,1	0,7	1,4	4,9	1,5	0,8	1,3	0,9	0,8	0,0	0,7
MgO	2,5	0,8	0,8	1,1	10,9	3,3	0,9	1,3	1,1	3,1	7,4	2,4	1,7	2,1	7,1
K2O	0,3	0,8	0,5	1,4	0,6	0,9	1,6	0,8	1,8	1,7	0,9	1,5	1,9	0,7	0,6
Na2O	0,0	0,0	0,8	0,0	12,1	0,0	0,0	1,3	0,0	0,9	1,4	0,0	1,4	0,2	0,3
BaO	0,0	0,0	0,1	0,0	0,3	0,0	0,0	0,1	0,0	0,0	0,1	0,0	0,1	0,0	0,0
MnO	0,2	0,0	0,1	0,0	0,1	0,1	0,0	0,1	0,0	0,0	0,1	0,1	0,1	0,0	0,6
SrO	0,1	0,0	0,1	0,0	0,3	0,0	0,1	0,1	0,0	0,1	0,1	0,2	0,1	0,0	0,1
ZrO2	0,0	0,1	0,1	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,1	0,0	0,0	0,0
CuO	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Nb2O5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
P2O5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
V2O5	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Cr2O3	0,0	0,1	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Cl	0,0	0,0	0,0	0,0	0,5	0,1	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0
Total Measures	94,4	89,4	98,6	91,8	100,8	88,0	96,3	93,3	89,4	92,2	95,2	89,3	89,7	97,6	100,8
LOI	-0,4	0,8	1,6	0,8	6,0	11,6	2,0	1,6	1,5	1,3	-	-	3,9	0,0	-78,2
SiO2+Al2O3+ Fe2O3	51.3	83.3	67.7	85.3	15.2	41.7	77.4	80.7	82.5	66.7	50.4	73.9	79.1	28.6	49.2
FA Type	C	F	?	F	C	C	?	F	F	C	C	F	F	-	-

TABLE 7 CHEMICAL COMPOSITION IN %, AND LFA CHARACTERISTICS

A large variation in the chemical composition of de LFAs can be observed (Table 7). The heterogeneity that was discussed in § 2.2 can be observed in these results. No relation between the composition and country can be found, because the differences are very specific in every region. Each lignite field has its specific geological character which can be found in the LFA. To divide the

LFA in F and C class fly ashes, the combined shares of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ are calculated. Both the F and C class fly ashes are well represented in these samples.

Besides the chemical characteristics, the physical characteristic play an important role in the function of the LFA. The smaller the particles are, the larger the total surface area and thus the higher the reactivity of the LFA

is. In addition to the LFA samples, three reference samples (cement, GGBFS and HFA) that were used, were also characterized. This was done in order to identify the main differences with LFA. The cement was required to create the LFA-cement prisms. To compare the characteristics of HFA and LFA, an HFA sample from Italy was characterized. No concretes were constructed with this HFA. The GGBFS (iron ore oven residue) was used in the recipe for geopolymers.

Since there was not enough time and financial means to include all these LFAs in the tests that determine the applicability in concrete and the leaching behavior in the deposits, six different types of LFA were selected to conduct the further research with. The first criteria on which the selection of the of the obtained LFA samples was based, was the date of possession. At a determined moment (1-5-2009) the

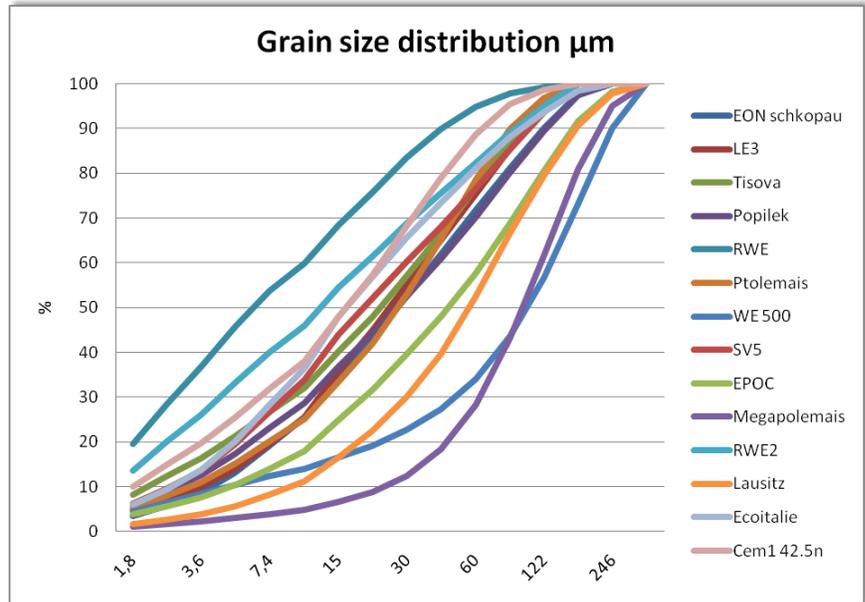


FIGURE 10 GRAIN SIZE DISTRIBUTION GRAPH (CUMMULATIVE BUILD UP)

Sample Name	FA Class	Obtained before 1-5-2009	LFA cement prism	Leaching	Geo-polymers
EON	C	X	X	X	X
LE3	F	X	X	X	X
Tisova	?	X	X	X	X
Popilek	F	X	X	X	X
RWE	C	X	X	X	
Ptolemais	C	X	X	X	X
WE500	?	X			
SV5	F	X			
EPOC	F	X			
Megalopolis	C	X			
RWE2	C				X
Lausitz	F				
Eco ita	F	X			
CEM1 42,5	-	X	X		
GGBFS	-				X

TABLE 8 SELECTED SAMPLES

construction of the LFA-prisms needed to begin, because the curing of these prisms takes 91 days. The LFA prisms that were collected before that date were compared on their characteristics. The six that were chosen all have a specific chemical composition. Three C type and two F type LFAs are represented (Table 8).

Tisova falls in between the two classes. The chemical composition of the other four LFAs all resembles another type of LFA. WE500 and SV5 resemble LE3, EPOC resembles Popilek and Megalopolis resembles Tisova. Another reason why these six LFAs were chosen is that they all have a normal grain size distribution. As can be observed in Figure 10, none of

selected LFAs have a derogatory grain-size distribution. This excludes that large differences in the outcome of the tests are caused by variation in grain-size distributions. The only difference between the selection of samples for the LFA-cement prisms and the geopolymers is the RWE sample. The first sample that was sent by RWE, proved to be an incorrect sample. This fly ash was a rest product from the paper industry. This was discovered after the LFA-cement prisms were constructed and leaching tests were conducted. Unfortunately the results of the tests done with the first RWE sample are not very relevant in this research. When the second correct sample was obtained there was not enough time to construct and test new LFA-cement prisms and conduct new leaching tests with the RWE2 sample. Geopolymer test were done with the RWE2 sample, because does represent an important source of LFA and the test were done at a later time.

5 LFA applicability

In this chapter the applicability of LFA in concrete will be assessed. This is done based on the two most critical parameters; mechanical applicability and processability. Although there are many other factors that determine the applicability of concrete (§3.3), these factors give the best indication on the applicability of the concrete.

5.1 Mechanical applicability

The mechanical applicability is determined by the strength of the mortar. Both flexural and compressive strength are measured to get an indication of the mechanical performance of the various types of LFA mortars. For each type of LFA-prism three different cement replacement percentages have been tested (respectively 15%, 30% and 45%). In Table 9 average values of three flexural strength tests and six compressive strength tests according to EN 196-1 are presented.

Prisms	Flexural strength av MPa 28 days	Compressive strength av MPa 28 days	Reference compressive strength %	Flexural strength av MPa 91 days	Compressive strength av MPa 91 days	Reference compressive strength %
100% CEM I 42,5 R	7,8	61,4	100	8,4	67,6	100
15% LE3 85% CEM I	6,6	54,6	88,8	8,6	66,0	97,6
30% LE3 70% CEM I	6,9	44,5	72,4	8,1	63,1	93,4
45% LE3 55% CEM I	5,8	32,3	52,6	7,4	49,5	73,1
15% E-on 85% CEM I	7,9	53,5	87,1	8,7	61,2	90,4
30% E-on 70% CEM I	7,5	47,4	77,2	8,4	52,8	78,1
45% E-on 55% CEM I	6,1	39,7	64,6	7,8	49,6	73,4
15% Popilek 85% CEM I	7,6	55,6	90,6	8,8	63,0	93,2
30% Popilek 70% CEM I	4,3	41,4	67,4	8,3	59,5	88,0
45% Popilek 55% CEM I	5,2	29,6	48,2	7,2	45,2	66,9
15% Tisova 85% CEM I	8,8	55,8	90,9	8,9	63,3	93,6
30% Tisova 70% CEM I	8,3	51,4	83,7	9,1	57,5	85,1
45% Tisova 55% CEM I	7,8	48,8	79,4	8,4	52,2	77,1
15% RWE 85% CEM I	7,8	52,1	84,8	8,1	60,1	88,8
30% RWE 70% CEM I	5,1	39,8	64,7	6,0	48,2	71,3
45% RWE 55% CEM I	3,8	24,7	40,2	4,6	27,9	41,3
15% Ptolemis 85% CEM I	7,8	53,9	87,7	9,2	65,1	96,3
30% Ptolemis 70% CEM I	7,4	47,7	77,6	8,1	52,7	77,9
45% Ptolemis 55% CEM I	6,5	37,4	60,8	7,5	41,9	62,0
30% E-on w/b-f adapted	6,8	51,9	84,4	7,8	56,5	83,5
30% Popilek w/b-f adapted	6,5	41,7	67,9	8,8	53,8	79,5
30% Tisova w/b-f adapted	6,5	49,7	80,9	9,0	53,7	79,4

TABLE 9 STRENGTH LFA-CEMENT PRISMS ACCORDING TO EN 196-1

If the results of the individual measurements would have a difference of more than $\pm 10\%$ from the average value, it would not have been considered a correct measurement. Fortunately all measurements remained within this margin and an even distribution of the results was observed. The standard deviation was not measured because the statistical relevance with three flexural and six compressive measurements is minimal.

To compare the LFA mortars with conventional mortars the reference strength is calculated as well. This is done by dividing the compressive strength of the LFA-cement-prisms with the compressive strength of the conventional CEM I 42.5 prisms. In Table 9 we can see that the reference strength of most 91 day LFA-cement-prisms is higher than the 28 days prisms. This implies that the reaction of these prisms occurs slower than the reference CEM I 42.5 prisms. This observation gives an indication that a pozzolanic reaction with the cement is taking place (§2.2.2). Especially the F type LFAs (LE3 and Popilek) show a later strength development. Tisova which is in between C and F type seems to show a less rigorous, but similar development. The same can be said for C type EON, Ptolemais and RWE. These C type LFAs reach their strength faster than the F type LFAs but still have a slower development than CEM I 42.5 prisms, because the relative compressive strength of the C type LFAs is higher after 91 days than after 28 days. In order to visualize this Figure 11 was created. The compressive strength tests have shown that 5 out of the 6 samples that were tested, achieve more than 90% of the reference strength after 91 days, when replacing 15% of the cement by LFA. When 30 % is replaced 3 out of the 6 samples achieve over 85% of the reference strength after 91 days (the strength of the LFA-cement prisms is relative to this reference CEM I 42.5-prisms) (Figure 11).

In general, the relative compressive strength decreases with an increasing percentage cement replacement with LFA. This is the case with every type of LFA that was tested.

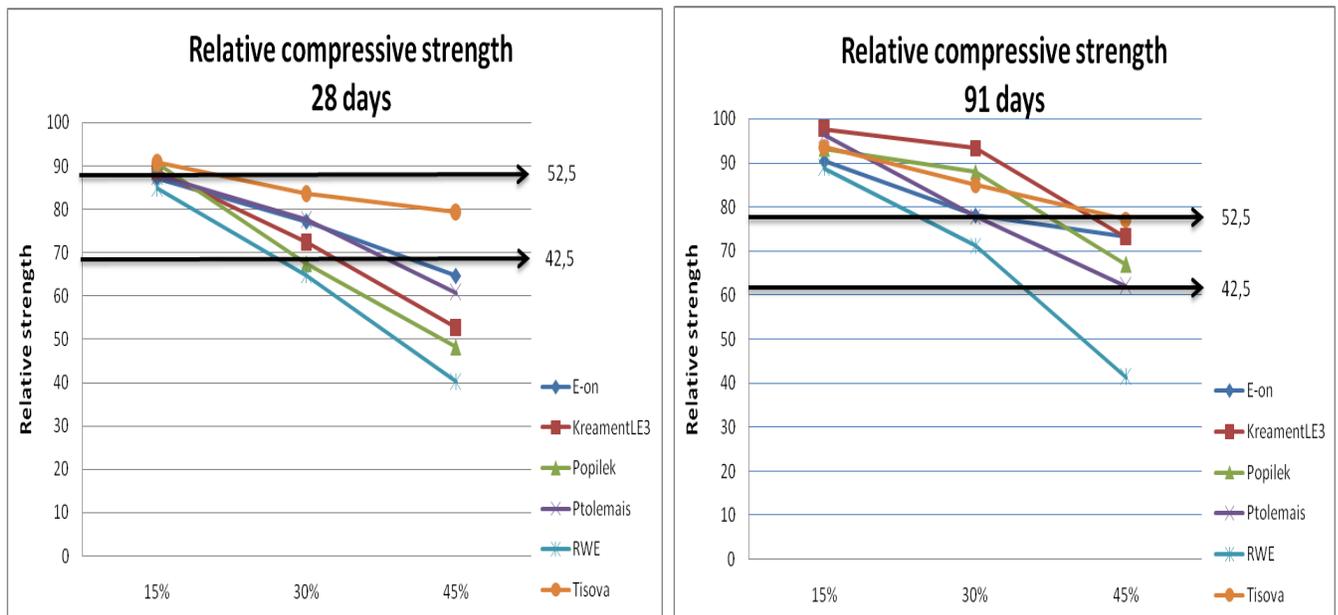


FIGURE 11 A: RELATIVE COMPRESSIVE STRENGTH AFTER 28 DAYS **B: RELATIVE COMPRESSIVE STRENGTH AFTER 91 DAYS**

To indicate the strength requirement for the cement types according to EN 197-1 (Table 3), two lines that represent the minimal strength requirements are shown in Figure 11. The compressive strength of the reference CEM I 42.5 prisms should be above the 42.5 line. In this case the average compressive strength result, of the CEM I 42,5 prisms, is represented by 100% of the relative strength. It can be concluded that the CEM I 42,5 prisms would meet the strength requirements of an 52,5 cement, which makes it strange that this cement is sold as an 42,5 instead of an 52,5 cement. We can see that some LFA-cement prisms in which 15% of the cement has been replaced with LFA also meet the 52,5 requirements after 28 days. The margin with the minimal requirement

is quite small. It is not known what the standard deviation would be if through time a large number of these tests are done. For the building industry it is essential to process products that have a constant quality and always meet the requirements. If the processed cement doesn't meet the requirements and is processed in a concrete construction of a building, the entire construction could be at risk.

This is why new types of cement have to be tested extensively before they can be processed in concrete. Also during production, quality checks of the cement have to be done on a regular base. Heterogeneity of the resources and inconsistency in the production process can lead to unpredictability of the quality of the end-product. As stated in § 2.2, this is also the case with the production of LFA. It is not likely that the LFA-cement mixtures that nearly meet the requirements, will constantly be above the required value. It could be argued that if the average of the six compressive strength tests is above 52,5 it would certainly meet the 42.5 strength class. Sadly the statistical evidence for this argument lacks.

When the results of the 28 and 91 days relative compressive strength are compared, an increase in strength can be observed. Most of the 30% LFA-cement prisms that have an average strength below 42.5 MPa after 28 days exceed the 42.5 after 91 days. The average compressive strength of the reference CEM I prisms increases 10% between 28 and 91 days, the average compressive strength of all the LFA-cement-prisms increases with 19,5% in the same period. This effect increases with a higher percentage of LFA in the mortar. On average 16,3% increase with 15% replacement, 22,7% with 30% and 25,3 with 45%.

5.2 Processability of the mortar

Not only is the strength important for the applicability of mortars (concrete), the processability is also an important factor. In order to process a mortar in a construction it has to be poured into a mould. If a mortar has the right consistency it will be easily poured into a mould. If the consistency is not within the processable range, the amount of water has to be adjusted until the required consistency is reached. However, the water/powder (W/P) ratio also affects the strength development of a mortar. In order to determine if a mortar is processable, the consistency is tested. All mortars were made with a standard recipe as prescribed in EN 196. This means that a set amount of powder (450g), water (225g) and sand (1350g) have been used to make the prisms. This mixture could be used to construct three mortar prisms. The replacement of CEM I with LFA can affect the consistency of the mortar. In order to check the consistency, before the mortars were poured in the prism moulds, the spread according EN 1015-3 was measured.

LFA	0%	15%	30%	45%
CEM I 42,5N ENCI	145			
LE 3		135	140	145
EON Schkopau		165	174	180
Popilek		153	153	160
Tisova		120	105	100
RWE		180	192	198
Ptolemais		127	108	100

TABLE 10 SPREAD IN MM ACCORDING EN 1015-3

Table 10 shows the spread of the mortars that were constructed for the EN 196-1 tests. Some LFA mortars show a large deviation from the reference mortar.

This deviation is both in the dry direction (low spread) as in the wet direction (high spread). To find out what the effects of the consistency are on the strength, the amount of water was adapted in three different mortars.

A new mortar of both a dry (Tisova) and a wet (EON) LFA mortar were made to determine the effects of water changes on the strength. A third mortar (Popilek), which had relatively less spread difference, was also tested for water requirement. Because the initial spread of the LE3 mortar was roughly the same as the reference mortar, it was assumed that the W/P of LE3 and the reference cement were in the same range. This was however not tested in a paste. RWE and Ptolemais samples were not tested for water requirements. The water requirement of these samples resembles those of EON and Tisova. Due to time and financial limitation no adapted water mortars were created from these LFA samples.

Because of the observed large variation in the consistency of the mortars, water demand of the LFA's had to be determined. To determine this, the spread of a paste of water and powder was tested (§ 3.2.2). This was done on the basis of the spread test of the mortars.

LFA	W/P paste	Spread paste mm	W/P mortar 30%	Spread mortar 30%
CEM I 42,5N ENCI	0,4	266	0,5	145
EON	0,25	252		
eon/cem	0,33	260	0,45	138
Tisova	1	242		
tis/cem	0,72	286	0,65	170
Popilek	0,33	288		
pop/cem	0,36	255	0,47	140

Because it takes a lot of material and effort to create a mortar with the right consistency, pastes of LFA and water were made to determine the water requirement of the LFA. Reference consistency was based on the spread of the reference cement paste. The spread of the paste was later translated to the spread of the mortar. The water demand of the LFA was determined by spread of the paste. To

TABLE 11 CONSISTENCY AT DIFFERENT W/P RATIOS

acquire the same consistency, the W/P was corrected until the spread of the LFA paste was within $\pm 10\%$ of the reference paste (240-290). This was a trial and error process. For the three LFAs of which mortars with corrected water were made, a paste with 100% LFA and a paste with 50% LFA and 50% cement was made. This was done to see if there is an effect of the combination between LFA and cement which alters the W/P requirement. Interacting effects between LFA and cement were not found.

To restrict the width spread of the paste another W/P ratio was chosen. The reference cement mortar had a W/P ratio of 0.5, the paste had a W/P ratio of 0.4. The W/P ratios of the LFA that were found in the tests could later be translated to water requirements for the mortar. It was found that the results of consistence of the paste could be translated in the consistency of the mortar. The influence from the sand that is added in the mortar is relatively constant. The Tisova paste however used more water in the paste than was calculated in the mortar. When the mortar was made with the calculated water it remained too wet (spread 170mm). The W/P had to be corrected from 0.65 to 0.57 to reach the required spread of the mortar. The AW mortars that were eventually created have been made with 30% LFA and 70% cement. These mortars were used to create the AW prisms. Because 30 and 70 % are the mean values in the EN 196-1 tests that were chosen to form the mortarprisms, these values were also chosen for the AW prisms.

Mortar AW 30%	W/P	Water gr.	LFA gr.	CEM I gr.	Sand gr.	Spread mm	C strength AW 28 days	C strength EN 196-1 28 days	C strength AW 91 days	C strength EN 196-1 91 days
Eon	0,44	200	135	315	1350	138	51,9	47,4	56,5	52,8
Popilek	0,47	210	135	315	1350	140	41,7	41,4	53,8	59,5
Tisova	0,57	255	135	315	1350	145	49,7	51,4	53,7	57,5

TABLE 12 STRENGTH DIFFERENCES WITH ADAPTED WATER PRISMS

If the W/P ratio in a conventional CEM I mortar or concrete decreases, the strength will increase. The water that is theoretically necessary to let all the cement react is about 0,25 of the weight of the CEM I (Ruijs 2005). The water cement ratio in the EN 196-1 is 0,5, which means that half the water in the mortar is not used in the reaction with cement. All the unused water will eventually evaporate and leave small hollow spaces that will weaken the concrete. This water is however needed to make the mortar processable and to make sure that all cement reacts. It was expected that the relation between W/P ratio and strength would also apply to the LFA-cement mortars. This relation can be seen with the EON and Tisova mortars (Table 12). The EON prisms that were produced with less water than the EN 196-1 standards achieved higher strength both after 28 and 90 days. The Tisova prisms that were produced with more water than the EN 196-1 standards achieved lower strength both after 28 and 90 days. This relation however doesn't apply to the Popilek prisms. These prisms that were produced with slightly less water than the EN 196-1 showed a lower strength development after 91 days. No fundamental theoretical explanation can be found for this deviating relation. It is assumed that an error in the production of the mortar or the testing of the prisms strength that caused this deviant relation. There are however no indications for this assumption. Because of this unexplainable result and the fact that only three different mortars were recreated with adapted water, no pronouncements can be made about the relation between the W/P ratios and strength development in LFA-cement-prisms.

In order to create a mortar or concrete that is easier to process, plasticizers are commonly used in concrete production. When plasticizers are added to the mixture, the spread and flow will increase. This way concrete, or mortar can be produced with less water. Because adding plasticizers would add extra complexity to the research, it was not added in the research. In practice, adding plasticizers to the mixture could provide a good option to steer the consistency and spread. Because both the chemical and physical properties of the different types of LFA have a high variation, their processability also varies.

5.3 Practical applicability

In every standard and regulation, the 28 days strength is determinative for the certification of binders. The 28 days strength can be important in the building process of some constructions. Within many other constructions there are limited strains in the concrete for the first 28 days. Early strength development is not equally important in every type of construction. If the standards would make a distinction between the fast and slow developing concretes, constructions wouldn't need to utilize fast developing concrete which is not required for the building process. This would

increase the potential for many types of industrial residues to be used in the building industry. Whenever waste material can be applied in a safe and useful way, both environmental and economical benefits can occur. However, policies and regulations are not always intended to stimulate this “recycling”.

Within the LCA difference analysis, it is not important which percentage of cement can be replaced with LFA. The functional unit on which the environmental impact is determined is 1 tonne of processed LFA. This implies that it does not matter if this 1 tonne is processed in 10 or 100 tonne concrete, because the environmental impacts of the other concrete ingredients are not included in that LCA.

The percentage of LFA that can be processed is however important to assess the viability of the option of processing LFA in concrete. If only a few percent of cement can be replaced with LFA, the advantages will not outweigh the disadvantages. It is not practical and economic to change logistic, production processes and concrete recipes for marginal benefits. Furthermore, if the amount of LFA that can be processed in 1 tonne concrete is known for every type of LFA, the total market for LFA in the concrete sector can be assessed. Based on the data that was generated it is difficult to make estimations about the potential for LFA within the European concrete market for various reasons:

1. Type of application: There are many types of concrete, all for different applications. Every application requires specific characteristics from the concrete that is used. For this reason the European concrete market is divers and the potential for LFA in this market is difficult to assess.
2. Amounts of various types of LFA: To get an indication of the total amount of LFA that is produced annually within Europe is difficult; to exactly map the production of every type of LFA is even more difficult. The suppliers of the LFA samples were asked to specify the annual production. Some of the suppliers specified the production of a single plant others of the whole lignite area. This makes it hard to get a picture on the various LFA streams.
3. Concrete quality: The LFA that seems to have a potential for processing in concrete, could run into potential problems that have not been tested. Some of these problems could affect the market potential for LFA.
4. Transport: Because LFA currently is a waste product, the price of LFA will be close to nothing. The transport of LFA though, isn't free of costs. If processing of LFA in concrete will be an economically viable option or not, will mainly be determined by the cost of transport. When the concrete production facility is in the proximity of the LFA producing location, it's more likely to be economical than if there is a large distance between the facilities. The European market for LFA in concrete will be affected by the transport costs.

6 LCA

This chapter will address the environmental impact of the different processing options. First of all the different elements of the dumping scenario [1] will be described. After that scenario the differences between concrete producing scenarios [2] + [3] are described. Finally the environmental impact of processing LFA in concrete [3] is compared with the reference situation [1] + [2].

The LCA of geopolymers will specifically be addressed in §7.3.

6.1 Dumping scenario [1]

The dumping scenario has three inputs: one material and two processes. LFA is the material that is deposited. Because LFA is considered a waste product, no emissions are allocated to its production. The LFA that is produced in the power plant has to be transported to the depositing site. This process is described as disposal. When the LFA is in the depositing site, there is still interaction between the site and environment. This process is described as depositing in §6.1.2. together these inputs form the inventory for the dumping scenario.

6.1.1 Disposal

After the LFA has been produced at the power plant, it has to be transported to the designated depositing site. There are four ways in which the LFA can be transported, which are described in §2.2.1. The specific distances from the power plant to the depositing site for the different types of LFA are unknown. A lignite producing and processing area is dynamic in its functions. The mining site from which the power plants receive lignite, as well as the depositing site where the LFA is disposed, can change in time. Therefore it is hard to determine the exact distances from power plants to the depositing sites. The choice of the means of transport will depend on these distances and the existing infrastructures that are available within the area. It would be inefficient to use a conveyor belt for a long distance and a train for a short distance. Because no information about these distances was obtained, assumptions on the distances were made based on the means of transport (Table 13).

Transport mean	Assumed distance to deposit	LFA sample
Conveyor	10km	Tisova, Popilek, Ptolemais
Pipeline	20km	LE3
Truck	30km	RWE
Train	40km	EON

Based on the distances in Table 13 the environmental impact of disposal can be calculated. The databases in Simapro provides data on the environmental impact per tonne/km for transport with pipeline, truck and train. The respective

TABLE 13 DISTANCES TO DISPOSAL OF THE DIFFERENT TRANSPORT MEANS

records that have been used are *Pipeline onshore U ETH-ESU 96 database* for pipeline transport, *Transport, coal freight, rail/CN U Ecoinvent* for train transport and *Transport, lorry >32t, EURO4/RER U Ecoinvent* for truck transport.

There is no record for conveyor transport in this database. Therefore the environmental impact of conveyor transport had to be calculated based on the information in an energy audit for conveyor belts (Marx 2005). Marx calculated that the energy consumption of conveyor belt transport is about 0.1kWh/tkm. It is assumed that the electricity that is used will be generated in lignite power plants. Other processes that contribute to the environmental impact of conveyor, like the production of the conveyor itself, have not been included in the record. The assumed distances were integrated in the records, in order to calculate the environmental impact for each option.

Impact category	Unit	Conveyor 10tkm	Pipeline 20tkm	Truck 30tkm	Train 40tkm
Abiotic depletion	kg Sb eq	9,24E-03	1,62E-03	2,69E-02	1,12E-02
Acidification	kg SO2 eq	9,06E-03	1,67E-03	1,38E-02	1,93E-02
Eutrophication	kg PO4-eq	2,33E-04	5,50E-05	2,58E-03	2,02E-03
Global warming (GWP100)	kg CO2 eq	1,23E+00	2,22E-01	3,47E+00	1,76E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	1,94E-09	9,26E-08	5,51E-07	1,22E-07
Human toxicity	kg 1,4-DB eq	1,86E-01	7,46E-02	9,83E-01	6,50E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	1,55E-01	1,44E-02	2,47E-01	1,98E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	4,14E+02	4,51E+01	3,68E+02	3,28E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	1,43E-03	8,49E-04	1,16E-02	6,08E-03
Photochemical oxidation	kg C2H4	3,46E-04	7,01E-05	5,61E-04	7,25E-04

TABLE 14 ENVIRONMENTAL IMPACTS OF DIFFERENT DISPOSAL TRANSPORT OPTIONS

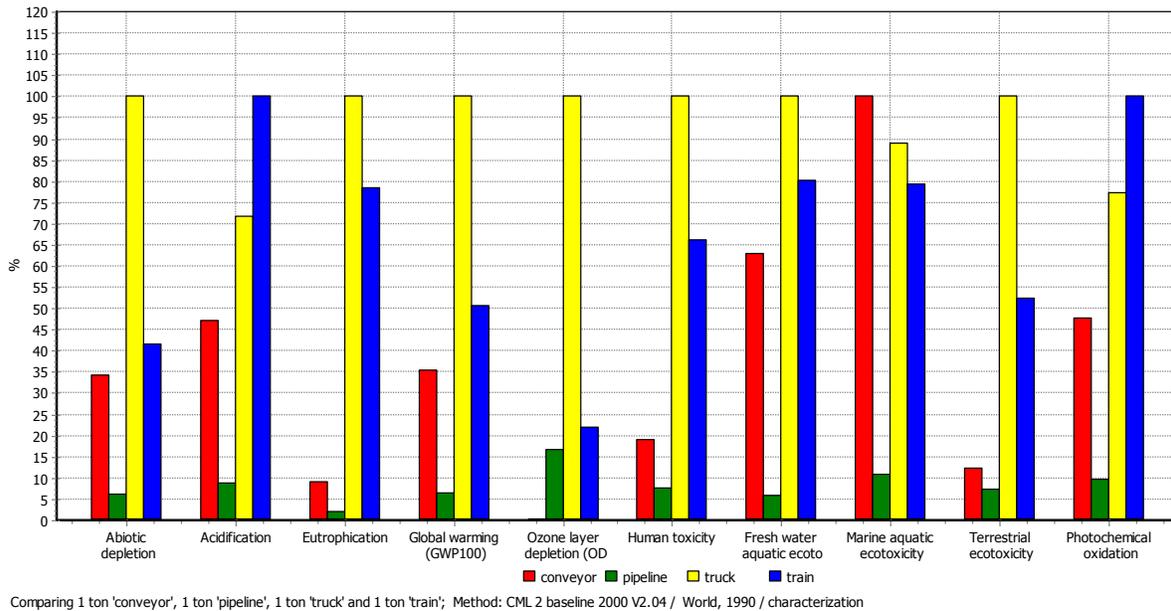


FIGURE 12 RELATIVE ENVIRONMENTAL IMPACTS OF DIFFERENT DISPOSAL TRANSPORT OPTIONS, CONVEYOR 10TKM, PIPELINE 20TKM, TRUCK 30TKM, TRAIN 40TKM

As can be seen in Figure 12 the truck and train have the highest impacts in almost every category. This could be expected because the distances of those transport options is larger. Because the transport of LFA requires energy, it's logical that CO₂ is produced in the process. The train is a more energy efficient in comparison with the truck for this type of transportation. This is why even with a higher distance the train still has fewer emissions. Probably the LFA is mixed with water before it is

transported in a pipeline. The LE3 LFA was transported with the waste water of the desulfurization installation. When the emissions of the pipeline transport are allocated on the bases of weight, the emissions that are presented in Table 14 have to be allocated to the LFA disposal. If water needs to be added intentionally to transport the LFA, the weight of the water has to be added to the transport load of LFA. This will increase the total impacts of pipeline transport. The impacts in Marine aquatic ecotoxicity of conveyor belt transport are the highest of all transport options. This is probably due to the fact that lignite-electricity is used to power the conveyor belt (see §6.1.2). If the pumps in the pipeline were also powered with lignite-electricity the emissions would probably be higher than they are now.

6.1.2 Depositing

After the material is disposed from the Lignite-fired power plant towards the depositing site, the depositing process begins. In this research this process has been described as interaction between LFA in the deposit and the environment. Because the effect of wind erosions are discarded (see §2.2.1), leaching of the LFA remains the only process which is assessed in depositing.

In order to assess the environmental damage caused by depositing of LFA, several methods can be used. In this research leaching tests were done (see §3.2.3). In the Ecoinvent LCA database there are also records for the depositing of LFA (*Disposal, lignite ash, 0% water, to opencast refill/DE U*). The method that was used to generate the emissions for this record was not found to be representative for this research as described bellow

Ecoinvent LFA depositing record (*Disposal, lignite ash, 0% water, to opencast refill/DE U*)

In the Ecoinvent record for lignite fly ash depositing, no leaching tests were done to determine the emissions of depositing LFA. The emissions were determined in the following way:

The emissions from an alkaline landfill with inorganic waste were measured during a certain time period. The chemical composition of the waste was determined before the waste was deposited.

Based on the measured emissions from the landfill the mobility of the different elements was determined. The information on the mobility of elements within an alkaline landfill is used to determine the leaching of an LFA landfill, by using the same transfer coefficients (Doka 2003). The chemical composition of the lignite is determined by laboratory analysis, and based on this composition the elements in the LFA are determined. These elements are multiplied with the transfer coefficients to determine the emissions of LFA depositing.

The problem with this approach is that a lot of site specific factors have been incorporated into the transfer coefficients. This leads to totally different results in comparison with the leaching test conducted in this research. The conditions within the fly ash deposits will have many differences. There are many conditional factors that will determine the actual leaching of an LFA deposit such as:

1. Disposal method: The way LFA distributed in the deposit, wet or dry distribution. In which way is it transported to the deposit; conveyor belt, truck, train or pipeline, with waste water from desulfurization installation. Important for the buildup of a deposit.

2. Weather conditions: Annual rainfall, sunshine, wind and temperatures. Research has shown that also temperature has large effects on the leachability of elements (Baba, Gurdal et al. 2006).
3. LFA permeability: The permeability of the fly ash determines the contact between LFA and water. It is influenced by the compacting of the fly ash. What is the water permeability through time? Does the LFA harden into an impermeable monolite material? What correlation can be made with the L/S ratio of the leaching tests?
4. Geological situation: Location and flow behavior of groundwater streams, effects of buildup of the deposit and ground layers under the deposit.
5. pH development through time: In which way does the pH within the deposit change in time. This also has to do with thickness of the LFA layer. The outside of the pack will be under the influence of weathering and will carbonate faster. This carbonization process changes the pH.
6. Concentration of elements: Differences in concentration will have an effect on the mobility. The mineral phase in which the elements occur, is also an important factor that determines when the elements will solute.
7. Leaching prevention methods: Which prevention methods are taken to prevent the leaching of harmful substances (sealing of the deposit for water)? For which period is the deposit open for all the weather elements?

The fact that these location specific conditions are incorporated in the transfer coefficient makes the Ecoinvent record unreliable. The method that was used doesn't represent the realistic situation. Furthermore, in this specific record a time scale of 60000 years was chosen (Doka 2003). The transfer coefficients on this time scale cannot be determined by measurements. To extrapolate the transfer coefficient to this time scale a formula was used. The result of this formula is that for almost every element the transfer coefficient will be 100% after 60000 years (see Appendix 2). If long term transfer coefficients are calculated in this way, complex chemical processes are being ignored. This method in turn results in very high emissions, especially on the long term. Because the time span of 60000 years was chosen, all the emissions are added up and produce relatively high emissions in the toxicity categories. In the CML impact categories: Abiotic depletion, Acidification, Global Warming, Ozone layer depletion and Photochemical oxidation no emission related to LFA disposal were found. These categories which had a zero value are not presented in the presented tables.

Ecoinvent Disposal, lignite ash		Long term emissions 60000 years			Short term emissions 100 years		
Impact category	Unit	LT/DE	LT/CZ	LT/GR	ST/DE	ST/CZ	ST/GR
Eutrophication	kg PO4 eq/1FU	5,27E-01	1,37E-01	1,77E-01	8,78E-04	2,29E-04	2,95E-04
Human toxicity	kg 1,4-DB eq/1FU	8,79E+02	6,14E+02	7,85E+02	1,30E+02	1,77E+02	2,26E+02
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	8,08E+02	8,09E+02	1,04E+03	1,33E+01	1,71E+01	2,19E+01
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	2,70E+06	1,89E+06	2,43E+06	5,41E+04	6,92E+04	8,81E+04
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	7,13E-02	1,86E-02	2,40E-02	1,41E-05	3,67E-06	4,75E-06

TABLE 15 EMISSIONS DISPOSAL PER TONNE LFA / ECOINVENT RECORD WITH DISTINCTION BETWEEN LONG AND SHORT TERM

It was interesting to see which emissions caused the impacts. The emissions in Marine aquatic ecotoxicity in the LT/DE record are 2,70E+06 kg 1,4-DB eq. Of those emissions in the DE record 1,65E+06 kg 1,4-DB eq is caused by the emission of Beryllium. This is due to the high characterization factor that beryllium has, the total emission of Beryllium was only 3 g/tonne LFA.

The transfer coefficient of Beryllium is 100% in 60000 years. However in the first 100 years it is only 0.15% (see Appendix 2). This means that the extrapolation formula that was used to determine the transfer coefficients has a large impact.

The Ecoinvent LFA disposal record (*Disposal, lignite ash, 0% water, to opencast refill/DE U*) was also modified by excluding all the long term emissions. Because the emissions in the record are specified in long and short term emissions, it was possible to adapt the record and exclude the long term emissions, which are also presented in (Table 15). It is peculiar that the author of this record makes a large effort to calculate the long and short term emissions and doesn't make two separate records. The record that has a timeframe of 60000 years is the only one that practically can be used by all the users and other records of the database.

Leaching test records (ECN)

In this research it was chosen to execute leaching shake tests in order to determine the emissions of LFA depositing. The method to conduct these leaching tests was constructed with Rob Comans of ECN (see Preface). Four different tests on six different LFA samples were done.

L/S 10 pH V: This test represents the situation that occurs when water comes into contact with LFA. Most LFA's have an alkaline pH. The mobility of the substances is dependent on the pH. The LFA's that are naturally acidic have been leached with alkaline additives to increase the pH up to 12.

L/S 10 pH Neutral: This test was done to simulate the effect of a change of the pH which occurs in a deposit. In time weathering can change the pH of an LFA deposit. This in turn changes the mobility of the elements. At set intervals within the 48 hours, the pH was measured and corrected with alkaline or acid additives.

L/S 10 pH X: This test represents the extreme condition in which natural situation for LFA's can get under influence of weathering. The pH of the LFA's that were naturally acidic (<7), have been leached with alkaline additives to increase the pH up to 12. The naturally alkaline LFA's (>7), have been leached with acid additives to decrease the pH to 4. At set intervals within the 48 hours, the pH was measured and corrected with alkaline or acid additives.

L/S 2 pH LFA: this test simulates the effects of limited contact between LFA and water. This can be caused by limited time or a very low permeability of the material.

These different tests all simulate another situation. The emissions of the test are presented in Appendix 3, they served as inventory for this LCA. It is not straight forward to translate the results of these tests into actual realistic emissions. The seven conditional factors that are mentioned above all have their influence in the actual leaching of the LFA deposit. Unfortunately only limited information on these factors on the researched deposits is known. It would require enormous efforts to collect information about these factors. After all this information would be gathered, a model would have to be made to translate this information in actual leaching results. Such a model would be useful but very complex. Until this moment there is no model that includes all these

factors concerning LFA deposits. Hans van der Sloot from ECN is currently working on a leaching model for fly ash deposits, in which more of this location specific conditional information is part of the input. At this moment such a model and the required input is not available, so the emissions have to be based on the shake tests that are executed.

The results of the leaching tests have to be translated into functional input for the LCA. In determining the emissions for 1 functional unit (1 tonne LFA) the time scale plays an important role. Leaching of elements is a constant process without a defined end. The actual disposal of LFA to the deposit is done at a specific moment, but the emission from the deposit to the groundwater is an ongoing process. Besides the quantity, the effects of long term emissions are highly uncertain. The cumulative emissions of the entire time scale are added up, and present 1 value in the different impact categories. Specifying the time of emission is not possible with this type of LCA analysis. In applying this method, the effect of the level of concentration of the different elements is discarded. The level of concentration has an influence on the damaging effect on organisms (toxicity). If for instance Molybdenum leaches out in very short time span, the concentration in the groundwater and thus the environmental impacts are high. On the other hand Barium is relatively immobile and will take more time to leach out (Appendix 2), so the concentrations in the groundwater will be relatively low. Based on this assumption a gradual leaching of Barium will not lead to high concentration in ground water, and the toxic effects will be limited. When the characterized contribution of the different elements to the total score of the EON pH N L/S 10 record (Table 16) was researched, Barium proved to have the highest contribution to the total score of Marine aquatic ecotoxicity. The ecotoxic effects of emissions are represented by the characterization values in different environmental impact categories of the CML 2 baseline 2000 scenario. Because all toxic elements eventually flow to the sea and ever toxicity category uses the same equivalents, the highest characterization values are found in Marine aquatic ecotoxicity (Table 15 and Table 16). Furthermore, there are uncertainties of the destiny of LFA deposits on the long term. We could recycle material that was once deposited, new areas could be built on LFA deposits, better leaching prevention methods could be implemented in or on top of new dumps. Because of the long term uncertainties a pH neutral scenario is constructed.

Some authors assume that inorganic landfills will reach neutral pH values (7) after a few hundred years (Quina 2009), but there are no measurements that can confirm this. What is known, is that roman concrete (approximatively 2000 years old) that was fully carbonized had a pH value of 8 (van der Sloot 2002). All the conditional factors that were mentioned earlier could affect these assumptions. Since there is no better model to predict the influence of such factors these leaching tests seem the way to predict future leaching. The pH N leaching test simulates the leaching if the pH would reach 7. Results from these tests are used to create pH N leaching model. To compare the results with a more extreme situation the results of the LCA of the pH X test are also shown in Table 16. Because it is not known how the pH of a deposit will develop in the long term, it cannot be predicted in which time span (if at all) this pH will be reached.

Leaching LFA pH N L/S 10							
Impact category	Unit	EON	LE3	Tisova	Popilek	RWE	Ptolemais
Eutrophication	kg PO4-eq/1FU	1,22E-03	2,30E-03	2,45E-03	1,13E-02	3,83E-03	2,14E-03
Human toxicity	kg 1,4-DB eq/1FU	1,63E+01	7,93E+00	2,56E+01	1,66E+02	1,41E+01	2,24E+01

Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	2,02E+01	8,09E+00	7,40E+01	4,75E+02	2,89E+01	3,53E+01
Marine aquatic ecotox.	kg 1,4-DB eq/1FU	2,55E+04	9,09E+03	6,69E+04	4,46E+05	3,02E+04	3,67E+04
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	1,49E-20	8,47E-21	6,24E-20	5,16E-19	2,64E-20	2,40E-20
Leaching LFA pH X L/S 10							
Impact category	Unit	EON	LE3	Tisova	Popilek	RWE	Ptolemais
Eutrophication	kg PO4-eq/1FU	2,75E-02	4,74E-03	3,06E-02	2,45E-03	2,75E-03	2,75E-03
Human toxicity	kg 1,4-DB eq/1FU	3,30E+01	5,05E+01	5,68E+01	5,43E+01	6,69E+00	2,48E+01
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	1,52E+02	1,25E+02	1,62E+02	8,03E+01	2,39E+01	1,37E+02
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	1,33E+05	1,20E+05	1,55E+05	8,36E+04	2,28E+04	1,13E+05
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	9,88E-20	2,14E-19	2,04E-19	1,45E-19	1,51E-20	5,70E-20

TABLE 16 EMISSIONS DEPOSITING PER TONNE LFA / BASED ON LEACHING TESTS

What conclusions can be drawn based on these results? The uncertainty in deposit buildup, deposit conditions, time span of emissions and characterization values in the different impact categories combined, undermine the value of the results. It can be concluded that the large variation in the physical and chemical characteristics of LFA also has its effect on the leaching behavior of the LFA. The geological situation in a specific mine will determine which elements will be present in the lignite. When this lignite is burned, the inorganic elements are transferred in the ashes. If these ashes are deposited, some of these elements will leach out towards the ground water. In Appendix 3 the specified emissions of these elements of each type of LFA is shown.

In reality EON emissions could be lower will because a pre-reaction has taken place before the LFA is deposited. The problem is that are no figures on the effect of this pre-reaction on leaching. The data, methods and models at this moment seem inadequate to draw sound conclusions on the environmental impact that LFA depositing has. The results of both the analysis of the Ecoinvent LFA disposal record and the results of the analysis of the leaching tests done within this research can be compared. The impact in Marine aquatic ecotoxicity of the *Disposal, lignite ash, 0% water, to opencast refill/DE U* record is 2,70E+06 kg 1,4-DB eq/1FU compared with 2,55E+04 kg 1,4-DB eq/1FU for the *Leaching LFA pH N L/S 10* record. This implies that the impacts in some categories can vary up to a factor of 100 depending on the time span that is chosen. The conclusions that can be made is that there is large a difference in the outcome of the different methods used.

Besides the uncertainty about the methods used to determine the emissions that are done by depositing LFA, there is also uncertainty about the characterization value of these emissions. The CML baseline, which is the most commonly used, has an infinite timescale. This has the greatest effect on the characterization value for marine aquatic ecotoxicity. When comparing the results of

Impact category	Unit	1 tonne deposited Tisova
Marine aquatic ecotox. 20a	kg 1,4-DB eq	3,49E+01
Marine aquatic ecotox. 100a	kg 1,4-DB eq	2,51E+02
Marine aquatic ecotox. 500a	kg 1,4-DB eq	1,34E+03
Marine aquatic ecotox. infinite	kg 1,4-DB eq	6,69E+04
Freshwater aquatic ecotox. 20a	kg 1,4-DB eq	6,94E+01
Freshwater aquatic ecotox. 100a	kg 1,4-DB eq	7,34E+01
Freshwater aquatic ecotox. 500a	kg 1,4-DB eq	7,34E+01
Fresh water aquatic ecotox. infinite	kg 1,4-DB eq	7,40E+01

TABLE 17 TISOVA PH N L/S 10 CML WITH TIME LIMITATIONS

Tisova pH N L/S 10 on the CML in which the effects of emissions are limited to a set timescale, the changes in the long term characterization factors for marine aquatic ecotoxicity can be observed. Because the toxic elements that are emitted to and soluted in water will eventually all flow into the sea, the long term characterization factor of Marine ecotoxicity is much higher than the freshwater ecotoxicity. The uncertainty on

the long term effect of these emissions is however much higher than the short term effects. Still the CML baseline with the infinite timescale is used because it is prescribed as a default in the CML 2 method.

It seems there is no accurate model or method to determine de emissions of an LFA deposit. It is however important to get some indication on the environmental effects of depositing LFA. Based on the extent of uncertainty and fundamental choices made, the results of the LFA pH N L/S 10 leaching methods seems to resemble the realistic situation the most of the analyzed methods. This is why the emissions of LFA pH N L/S 10 results will be used as a input in the dumping scenarios.

6.1.3 Environmental profile of dumping

When the impacts of the disposal and depositing of LFA are added up, the environmental impact of dumping can be shown (Table 18).

Impact category	Unit	EON	LE3	Tisova	Popilek	RWE	Ptolemais
Abiotic depletion	kg Sb eq/1FU	1,12E-02	1,62E-03	9,24E-03	9,24E-03	2,69E-02	9,24E-03
Acidification	kg SO2 eq/1FU	1,93E-02	1,67E-03	9,06E-03	9,06E-03	1,38E-02	9,06E-03
Eutrophication	kg PO4-eq/1FU	3,24E-03	2,35E-03	2,68E-03	1,16E-02	6,40E-03	2,37E-03
Global warming (GWP100)	kg CO2 eq/1FU	1,76E+00	2,22E-01	1,23E+00	1,23E+00	3,47E+00	1,23E+00
Ozone layer depletion (ODP)	kg CFC-11eq/1FU	1,22E-07	9,26E-08	1,94E-09	1,94E-09	5,51E-07	1,94E-09
Human toxicity	kg 1,4-DB eq/1FU	1,70E+01	8,00E+00	2,58E+01	1,66E+02	1,51E+01	2,26E+01
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	2,04E+01	8,11E+00	7,42E+01	4,75E+02	2,91E+01	3,55E+01
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	2,58E+04	9,14E+03	6,73E+04	4,46E+05	3,06E+04	3,71E+04
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	6,08E-03	8,49E-04	1,43E-03	1,43E-03	1,16E-02	1,43E-03
Photochemical oxidation	kg C2H4/1FU	7,25E-04	7,01E-05	3,46E-04	3,46E-04	5,61E-04	3,46E-04

TABLE 18 ENVIRONMENTAL IMPACT OF DUMPING 1 TONNE OF LFA (SCENARIO1)

The results of Table 18 show a large spread, especially in the toxicity categories. Popilek has the highest emissions in the toxicity categories. The impact of the emissions in these categories is about a factor of 50 higher than the impact of the lowest scoring LE3. Based on this variety of results it is hard to speak about dumping of LFA in general. Because Tisova seems to represents the average values of the dumping impacts the closest (Figure 13), the Tisova LFA was chosen as a representative LFA in upcoming comparisons and graphs. When the impacts in the toxicity categories of Table 14 and Table 16 are compared, it can be concluded that the contribution of these emissions on the total impact of the dumping scenario is so low that it doesn't have a significant effect on the end result of dumping 1 FU.

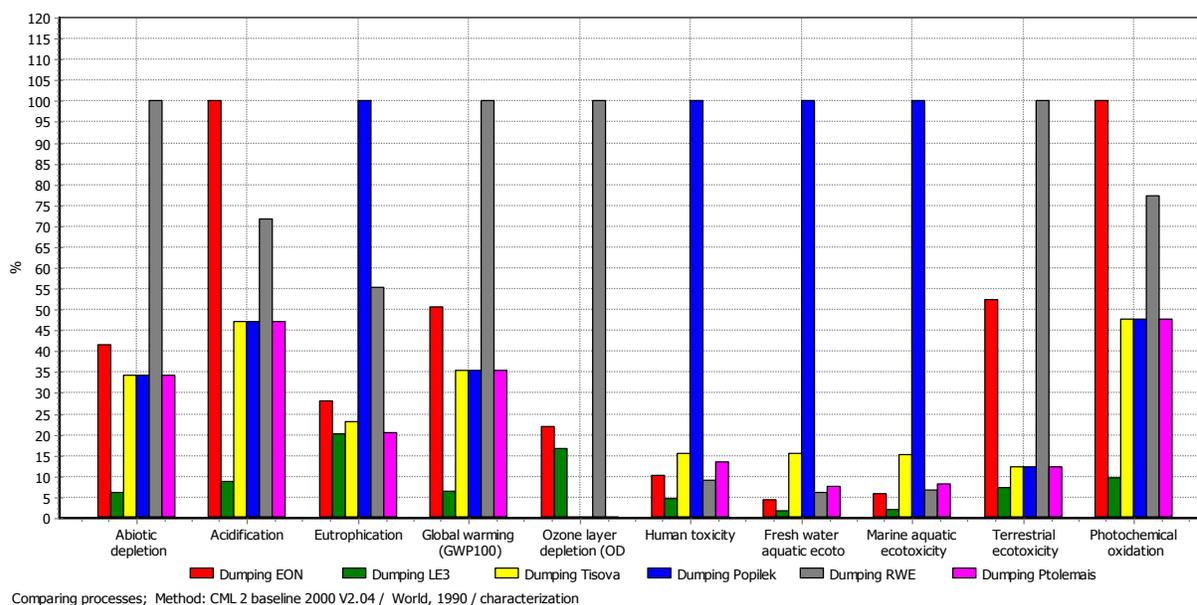


FIGURE 13 COMPARISON OF ENVIRONMENTAL IMPACTS OF DUMPING (SCENARIO1)

Depositing only has impacts in five of the ten categories. Therefore disposal (transport) accounts for all the impacts in the other five categories. The impact of disposal is relatively low in the toxicity categories. The three LFAs that are disposed by conveyor belt show the same impacts in any but the toxicity categories (Figure 13). Based on this it can be concluded that the differences that are being made in these categories are caused primarily by the disposal.

In the created conveyor record it was chosen to lignite-fired electricity as the energy source. Because the lignite power plant produces LFA, the *Disposal, lignite ash, 0% water, to opencast refill/DE U* record is integrated in the Ecoinvent record for lignite-fired electricity production. In §6.1.2 it is discussed that this record is unreliable, but through another record (lignite-fired electricity production) the emissions of this record are incorporated in the results of conveyor disposal. The results of conveyor disposal are again integrated in the results for dumping 1 FU (Tisova, Ptolemais and Popilek). EON and RWE samples which have low impacts in the toxicity categories, score relatively high in the other categories. This is due to the disposal by respectively train and truck

6.2 Concrete

Both scenario [2] and [3] are aimed towards concrete production. In scenario [2] concrete is produced in a conventional way, in scenario [3] it is produced with LFA as one of the ingredients. Because this LCA only focuses on the differences between the processing options, the environmental differences are addressed in this paragraph.

6.2.1 Preventing cement production

The main difference between scenario [2] and [3] is replacing a part of the cement with LFA. Because LFA is considered a waste product, no emissions of the LFA production process are allocated towards LFA. The replacement of cement with LFA means that less cement will have to be produced. In order to detect advantages of cement replacement, the environmental effects of cement production have to be known. By analyzing the Ecoinvent record for Portland cement production (*Portland cement, strength class Z 42.5, at plant/CH U*), the environmental effects of cement production can be identified. This record is however specific for the Swiss cement production.

Impact category	Unit	Portland cement 42.5N 1 tonne
Abiotic depletion	kg Sb eq	1,58E+00
Acidification	kg SO2 eq	1,14E+00
Eutrophication	kg PO4-eq	1,71E-01
Global warming (GWP100)	kg CO2 eq	8,35E+02
Ozone layer depletion (ODP)	kg CFC-11eq	2,29E-05
Human toxicity	kg 1,4-DB eq	4,50E+01
Fresh water aquatic ecotox.	kg 1,4-DB eq	5,11E+00
Marine aquatic ecotoxicity	kg 1,4-DB eq	1,05E+04
Terrestrial ecotoxicity	kg 1,4-DB eq	1,21E+00
Photochemical oxidation	kg C2H4	4,35E-02

TABLE 19 ENVIRONMENTAL IMPACTS OF PORTLAND CEMENT 42.5N PRODUCTION

The most important steps of the production process of cement have been addressed in §2.2.2.

Global warming, which is one of the high attention environmental themes, is caused by producing clinker. The use of energy and the chemical process transforming limestone into clinker both produce significant amounts of CO₂. In Appendix 4 a network of processes that cause Marine aquatic ecotoxicity is shown. This can be done to identify in which way the different processes contribute to the

environmental impact in each category. The impact of Marine aquatic ecotoxicity as well as most of the other impacts is caused by the energy use and the mining of limestone. This network analysis provides an insight in the most polluting processes of the production process. When these processes are known, prevention measures and alternatives can be developed.

6.2.2 Prevented dumping

The prevented emissions of dumping are also allocated towards the production of LFA-concrete in scenario [3]. When the LFA is mixed in concrete it is assumed to be processed (see §3.4.1). The reference processing is therefore avoided by the concrete production. If the values in Table 18 are put negative, they represent the prevented dumping.

6.2.3 Transport

Both LFA and cement will have to be transported from their production location towards the concrete production plant. It is assumed that, within Europe there are more cement producing than LFA producing facilities. This implies that the average distance between a concrete production

Impact category	Unit	Truck 100 tkm
Abiotic depletion	kg Sb eq	8,96E-02
Acidification	kg SO ₂ eq	4,61E-02
Eutrophication	kg PO ₄ -eq	8,58E-03
Global warming (GWP100)	kg CO ₂ eq	1,16E+01
Ozone layer depletion (ODP)	kg CFC-11eq	1,84E-06
Human toxicity	kg 1,4-DB eq	3,28E+00
Fresh water aquatic ecotox.	kg 1,4-DB eq	8,24E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	1,23E+03
Terrestrial ecotoxicity	kg 1,4-DB eq	3,87E-02
Photochemical oxidation	kg C ₂ H ₄	1,87E-03

TABLE 20 ENVIRONMENTAL IMPACT OF 100 TKM TRUCK TRANSPORT

plants and LFA production plants will be larger than the average distance between concrete production plants and cement production plants. Because no detailed information about these distances has been obtained, it is assumed that the average distance between the cement production and concrete production location is 100km. Furthermore an average distance between the LFA production and concrete production location of 200km is assumed. This implies that the difference between these distances is 100km. It is assumed that both LFA and cement are transported by truck to the concrete production location. Similar type of vehicles (silotrucks) can be used to transport LFA and cement (*Transport, lorry >32t, EURO4/RER U Ecoinvent*). In the difference analysis the transport of 100 tonne/km is added to LFA-concrete production scenario [3]. The environmental impact of this transport is presented in Table 20.

plants and LFA production plants will be larger than the average distance between concrete production plants and cement production plants. Because no detailed information about these distances has been obtained, it is assumed that the average distance between the cement production and concrete production location is 100km. Furthermore an average distance between the LFA production and concrete production location of 200km is assumed. This implies that the difference between these distances is 100km. It is assumed that both LFA and cement are transported by truck to the concrete production

6.3 Environmental benefits of scenario [3]

6.3.1 Environmental profile

Scenario [3] prevents both the production of cement and the dumping of LFA. Therefore the impact values of production of cement and the dumping of LFA are negative. Table 21 shows the different elements that contribute to the environmental impact of 1FU Tisova processed in concrete.

Impact category	Unit	Total	Truck 100 km	Dumping Tisova pHN	Portland cement
Abiotic depletion	kg Sb eq/1FU	-1,49E+00	8,96E-02	-9,24E-03	-1,58E+00
Acidification	kg SO ₂ eq/1FU	-1,11E+00	4,61E-02	-9,06E-03	-1,14E+00
Eutrophication	kg PO ₄ -eq/1FU	-1,65E-01	8,58E-03	-2,68E-03	-1,71E-01
Global warming (GWP100)	kg CO ₂ eq/1FU	-8,25E+02	1,16E+01	-1,23E+00	-8,35E+02
Ozone layer depletion (ODP)	kg CFC-11 eq/1FU	-2,11E-05	1,84E-06	-1,94E-09	-2,29E-05
Human toxicity	kg 1,4-DB eq/1FU	-6,75E+01	3,28E+00	-2,58E+01	-4,50E+01
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	-7,84E+01	8,24E-01	-7,42E+01	-5,11E+00
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	-7,66E+04	1,23E+03	-6,73E+04	-1,05E+04
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	-1,17E+00	3,87E-02	-1,43E-03	-1,21E+00
Photochemical oxidation	kg C ₂ H ₄ /1FU	-4,20E-02	1,87E-03	-3,46E-04	-4,35E-02

TABLE 21 ENVIRONMENTAL IMPACTS OF PROCESSING 1 FU TISOVA IN CONCRETE

The total scores of each impact category represents 1FU, which means the environmental impacts of processing 1 tonne of Tisova in concrete. If we want to calculate the values for the FU of the other LFAs, the results dumping Tisova in Table 21 have to be replaced with the impact results of dumping of the relevant LFA presented in Table 18. These values should be put negative in order to represent prevented emissions. The truck transport and the prevented cement do not change for other types of LFA. Results of the 1FU for each individual LFA are presented in Appendix 5.

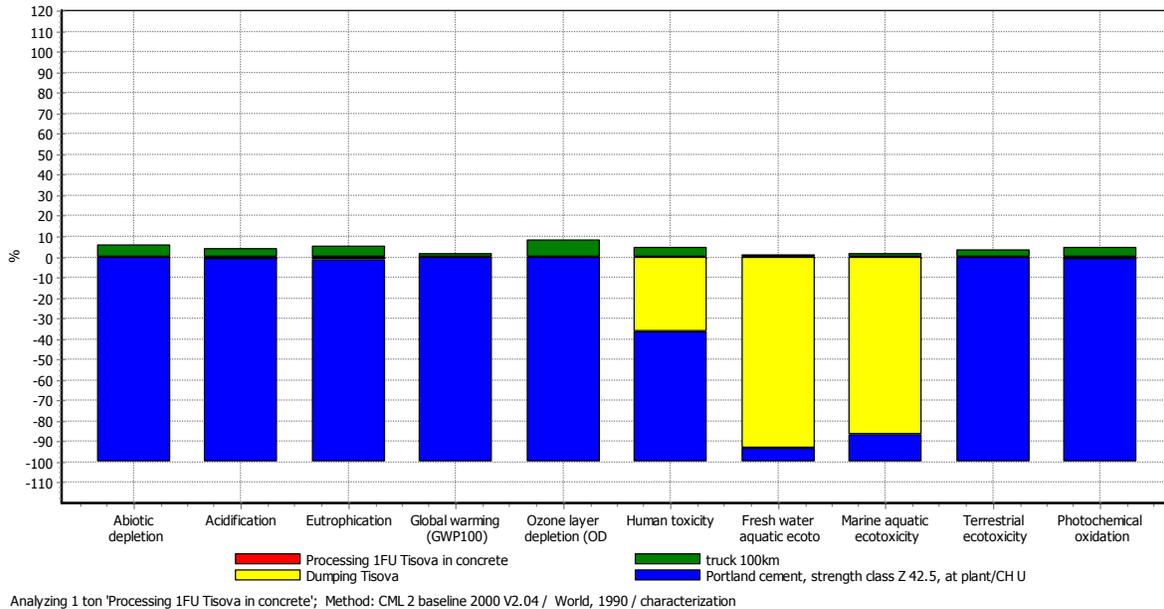


FIGURE 14 COMPARISON OF THE DIFFERENT PROCESSES CONTRIBUTING TO THE ENVIRONMENTAL IMPACT OF 1FU

In order to get an idea about the contribution of the different processes in the impact categories, the graph in Figure 14 was constructed. It can be concluded that the prevention of producing cement has a higher (negative) value for almost every impact category. Only for Fresh water aquatic ecotoxicity and Marine aquatic ecotoxicity the prevention of emissions is higher for dumping of Tisova. Depositing of LFA only has impacts in five categories (Table 16). In the other categories the only prevented impact of dumping is caused by the prevention of the disposal transport. These impacts are however relatively insignificant and therefore do not appear in the graph. The same can be stated for the extra transport that is needed to cover the larger transport distances between LFA production and concrete production. The contribution of the extra 100 km truck transportation is 11,6 kg CO₂-eq, in comparison with 835 kg CO₂-eq of preventing cement production. If the difference in transport distance was even larger it would still be interesting, from a CO₂ perspective, to use LFA in concrete. If the transport difference would be 500km, it would still only be 7% of the prevented CO₂-eq of cement production. It seems that the environmental impact of the extra transport of LFA will not be a determinant factor in the comparison of processing options. The environmental impacts of the other LFAs will show somewhat the same picture. The results of Popilek show a relatively much higher impact in the toxicity categories, whereas the other LFAs show a slightly lower impact in these categories (Appendix 5).

In order to make a comparison between the impacts of the different categories normalization has been done. Adding normalization to the results of each category makes it able to compare the significance in the contribution of the different impact categories. The end-result however possesses a even higher degree of uncertainty than the characterized results. In Figure 15 the normalized results of 1FU Tisova are presented.

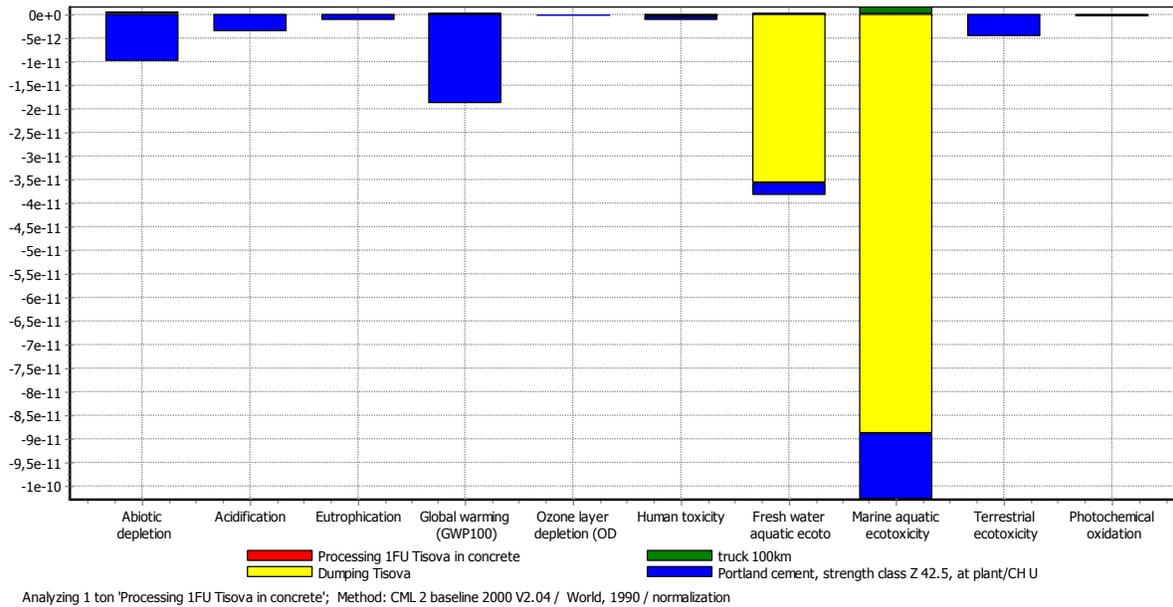


FIGURE 15 NORMALIZED RESULTS OF THE CHARACTERIZED IMPACTS OF PROCESSING 1FU TISOVA IN CONCRETE

This normalization step makes it clear in which impact categories the process or product relatively contributes the most to the average emission profile of a European citizen. In this case the prevented impact by processing LFA (Tisova) in concrete is represented. The highest contribution to the average environmental profile are made by Marine aquatic ecotoxicity and Fresh water ecotoxicity. This is caused by the fact that dumping is prevented. The impact on Global warming, which is caused by the fact that cement production is prevented, also seems significant. Based on the fact that the prevention of cement production, and the need for 100 tkm extra truck transport, are equal for all types of LFA, the relative impact is mainly determined by the prevented dumping. Therefore the total impacts of dumping determines the differences between the LFAs. After normalization, these differences only seem significant in two categories, respectively: Freshwater ecotoxicity and Marine aquatic ecotoxicity. The relative impact of the disposal transport (which is included in dumping) therefore seems minor. If we neglect the insignificant differences in the disposal transport, it can be concluded that preventing the dumping of LE3 has the least impact and preventing dumping of Popilek has the highest impact (Table 18). Based on the environmental profile of the processes that were modeled, it could be expected that the relative high impacts would occur in these categories. There are no known processes in dumping of LFA and production of cement that cause Ozone layer depletion and Photochemical oxidation. In the other categories like Acidification and Eutrophication there are relative minor impact reduction. These impact reductions are probably caused by indirect processes, such as the

production of capital goods that are used in the production of cement. The Ecoinvent database is very extensive in including all the processes that lead to the eventual end-product. Therefore impacts in unexpected categories can occur. All the normalized values of the different types of LFA are presented in Appendix 5.

7 Geopolymers

Besides the replacement of cement with LFA in current conventional concrete mixtures, a new and innovative approach to concrete production is researched as well. In this chapter the possibilities of using LFA as a raw material for geopolymers is assessed. Due to the different nature of the material and testing methods that were used, a separate chapter has been devoted to geopolymers. All the elements of the geopolymer research are presented in this chapter.

7.1 Geopolymers; a general description

Geopolymers are defined by Panias as “Inorganic polymeric materials, firstly developed by Joseph Davidovits in 1970s. Geopolymerization involves a chemical reaction between alumino-silicate oxides and alkali metal silicate solutions under highly alkaline conditions, yielding amorphous to semi-crystalline three-dimensional polymeric structures, which consist of Si–O–Al bonds”(Panias, Giannopoulou et al. 2007). Geopolymers are a new type of binders that can be used to create a hardened concrete-like material. (Chindaprasirt, Jaturapitakkul et al. 2009).

Fly ashes can be used as a raw material for geopolymers. Up till now the research mainly focused on the use of HFA as the main material to create geopolymers. In Australia a study on geopolymers from LFA has been done (Bankowski, Zou et al. 2004). The main emphasis of this research was reduction of metal leaching of LFA, not creating geopolymers for useful applications.

In the Netherlands, Henk Nugteren of the TU Delft is the specialist in the area of geopolymers. Together with Mr. Nugteren several practical test to determine the applicability of LFA in geopolymers were composed. The recipes that were used were based on experiences with HFA. Potassium-silicate was used as the alkali activator. Potassium-hydroxide was added to further increase the pH. This mixed product is referred to as Ksil. The high pH environment is a condition in which Si and Al solute well. When Si and Al are soluted they tend to form amorphous bonds. These bonds fulfill the binding function. Up till now it is not exactly clear what the roles of other elements in these amorphous structures are (Cox, Nugteren et al. 2008).

7.2 Methods and results

In order to test the performance of geopolymer-concrete, geopolymer pastes were made at the TU Delft. They have the expertise and facility to construct these materials. Small cylinders (diameter 30mm, height 30mm) with Geopolymerpaste were left to set for 28 days, after which compressive strength tests were conducted. These compressive strength tests were carried out at B|A|S, where the specific machinery to conduct these tests was available.

When applicable geopolymers with LFA will be created, a specific recipe for every different type of LFA will have to be developed. Each type of fly ashes tends to react differently to the alkaline in the Ksil. Because only indicative tests were done, a standard recipe based on previous experiences with

Ingredient	Amount
Fly Ash	60gr 46%
GGBFS	30gr 23%
Ksil	20gr 15,5%
Water	20gr 15,5%

TABLE 22 GEOPOLYMER RECIPE

HFA was used. The standard recipe that was used to start examining the applicability of LFA in geopolymers is shown in Table 22. This recipe has a W/P ratio of 0.44 because the Ksil is a fluid which is calculated as water. Consistency and spread of the geopolymer pastes were not tested in the same way this was done with the LFA-cement mortars. The equipment to test the consistency was not available at the TU Delft. Furthermore, geopolymers have a different texture and in practice they will probably be processed in another way as conventional cement pastes/mortars. One of the characteristics of some geopolymers that was observed is a thixotropic flow behavior. This means that the paste becomes liquid again when it is shaken at a certain frequency. In practice this will have a lot of implications regarding usage in the building industry. Further research is needed to examine this phenomenon.

In conventional cement, binding time regulators (retarders), are used to prevent the material from hardening before it is processed. Gypsum is the retarder that is normally used to control the binding time of cement. It is not known if gypsum has the same effect with geopolymers. Further research is required to determine which retarders can be used to control the binding time of geopolymers.

The tests that are done, have to give an indication on the potential of using geopolymers as an alternative for cement. The end product will be applied, it will have to meet all safety environmental health strength requirements. This is beyond the scope of this research.

Eventually two cylinders of every mixture were made. The average value of the results of the compressive strength tests are presented in Table 23. Based on this outcome it can be concluded

Sample	FA Class	Compressive strength av N/mm ²
EON	C	72,6
LE3	F	41,4
Tisova	?	88,3
Popilek	F	66,1
RWE2	C	-
Ptolemas	C	19,5
CEM I	-	33,7

TABLE 23 GEOPOLYMER STRENGTH TESTS

that each type of LFA has a different reaction with the other ingredients. This in turn leads to different performance of the end product. The RWE2 geopolymer is a brittle product which doesn't even give a reading on the compressive test bench. On the other hand the Tisova geopolymer exceeds all expectations in terms of strength development. The LFA-geopolymers show a large variation in strength development. Because geopolymers consist of Si-Al bindings it would be expected that F class LFAs would show a higher strength development than C class LFAs. This relation can however not be observed from these strength tests. Although only indicative tests were done, the results show promising enough to

further investigate the potential of geopolymers.

A reference CEM I cylinder was constructed to compare the performance of conventional cement binder with geopolymers. The cylinder was made from a cement paste with a W/P ratio of 0.44. This is the same W/P ratio which the geopolymer pastes used. In comparison with the LFA-geopolymers, the CEM I cylinder only has about 40% of the compressive strength of the Tisova-geopolymer. Although these were only indicative tests in which consistency and other important factor aren't taken into account, it is shown that further research in LFA-geopolymers could provide successful results.

7.3 LCA

The alkaline activator that is used to produce geopolymers is Ksil. The Ksil (K_2SiO_3) is produced by melting K_2CO_3 with SiO_2 . This Ksil is then soluted in water and enriched with KOH. The production of K_2CO_3 , KOH and the melting of K_2CO_3 with SiO_2 are all energy intensive processes that produce CO_2 .

The K_2CO_3 is produced by mining Sylvinite. It contains NaCl and KCl which have to be extracted and purified. Electrolysis is used to produce KOH from the KCL, to produce K_2CO_3 the KOH will be carbonized.

There are 5 production steps in which emissions are being emitted:

1. Extracting KCL from Sylvinite
2. Electrolyzing KCL to produce KOH
3. Carbonizing KOH to K_2CO_3
4. Melting K_2CO_3 and SiO_2 to K_2SiO_3 and CO_2 (two sources of CO_2 , burning of natural gas for melting and CO_2 from the reaction).
5. Soluting K_2SiO_3 and adding KOH

All these production steps were integrated in the LCA model. PQ Europe, which is one of the largest Ksil producers in Europe, provided detailed information about the production process. The K_2CO_3 is purchased from another producer in the chemical industry. Information on the production process of K_2CO_3 and KOH were found in the Ecoinvent database. The combination of the information from PQ with data from the Ecoinvent database (*1.Potassium hydroxide, at regional storage/RER U 2.Potassium carbonate, at plant/GLO U 3.Sand, Quartz, in ground 4.Heat, natural gas, at industrial furnace >100kW/RER U*) provided the required information to create a new Ksil record in Simapro. With this record the emissions during the Ksil production process could be calculated.

The recipes of the geopolymers that were made also contained GGBFS, which also is an industrial rest product. This GGBFS was a rest product from Corus iron ore ovens in the Netherlands. In most LCA studies GGBFS is considered a waste product and no emissions are allocated to its production. In order to determine the environmental impact of the GGBFS, the price has to be known. Within the steel production process, both steel and GGBFS are produced. For every 1000kg of steel about 200kg of GGBFS is produced. A distribution of the emissions from this production process will be done on the basis of an economic allocation. In order to execute this allocation the prices of both steel and GGBFS have to be known. The prices of steel and GGBFS are however dependable on a lot of factors. The steel price depends on an international market of demand and supply and is subject to fluctuations. The market for GGBFS is not transparent. Both producers (Corus) and buyers (ENCI) are not willing to give information about prices of GGBFS. Contracts between producer and suppliers are confidential in this market. There are small parties that trade GGBFS, but it is hard to determine what the steel producer receives for this product. Market prices of granulated GGBFS are estimated to be around €30/tonne. This is based on the price of cement in comparison with GGBFS cement and the retail price of milled GGBFS from ORCEM. With current steel prices around €600/tonne the emissions can be calculated in the following way:

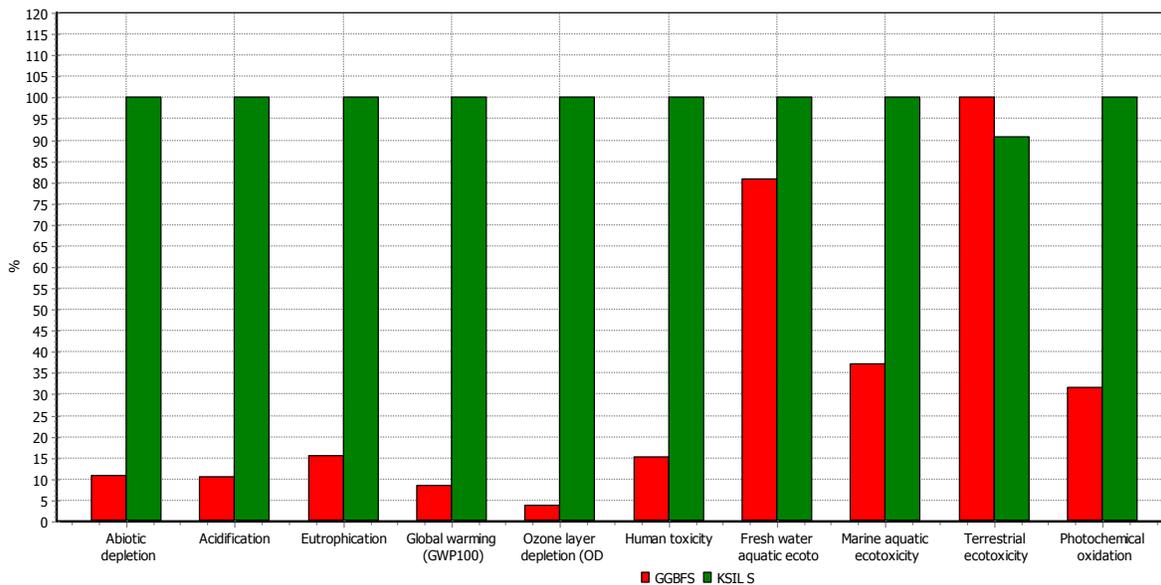
The total return on the production is estimated $(600 \times 1) \text{ €}600 + (30 \times 0.2) \text{ €}6 = \text{€}606$. The steel can be accounted for 99% of the emissions and the GGBFS for 1%. But the emissions of 1tonne GGBFS is 1% of the total emissions divided by 0.2 = 5% of the total emission of the production.

In the LCA of steel (*Cast iron, at plant/RER U*), the disposal of GGBFS was removed from the record. This was done to prevent that the emissions from depositing are included in the scenario in which GGBFS is used in geopolymers.

The two ingredients of geopolymers that contribute to the environmental impact are Ksil and GGBFS. The emissions that are done in the production of 1 kg Ksil and GGBFS have been calculated based on the described methods and are presented in Table 24. Figure 16 visually presents the differences in environmental profiles. The use LFA in the recipe will reduce the environmental impact, because the dumping of LFA is prevented.

Impact category	Unit	GGBSF 1 tonne	KSIL 1 tonne
Abiotic depletion	kg Sb eq	8,33E-01	6,36E+00
Acidification	kg SO2 eq	3,46E-01	2,76E+00
Eutrophication	kg PO4 eq	3,91E-02	2,12E-01
Global warming (GWP100)	kg CO2 eq	9,01E+01	8,75E+02
Ozone layer depletion (ODP)	kg CFC-11 eq	3,02E-06	6,72E-05
Human toxicity	kg 1,4-DB eq	5,79E+01	3,15E+02
Fresh water aquatic ecotox.	kg 1,4-DB eq	5,54E+01	5,71E+01
Marine aquatic ecotoxicity	kg 1,4-DB eq	5,31E+04	1,19E+05
Terrestrial ecotoxicity	kg 1,4-DB eq	4,07E+00	3,08E+00
Photochemical oxidation	kg C2H4	5,24E-02	1,38E-01

TABLE 24 CHARACTERIZED ENVIRONMENTAL IMPACTS OF KSIL AND GGBFS



Comparing 1 ton 'GGBFS' with 1 ton 'KSIL S'; Method: CML 2 baseline 2000 V2.04 / World, 1990 / characterization

FIGURE 16 COMPARISON OF ENVIRONMENTAL IMPACT BETWEEN KSIL AND GGBFS

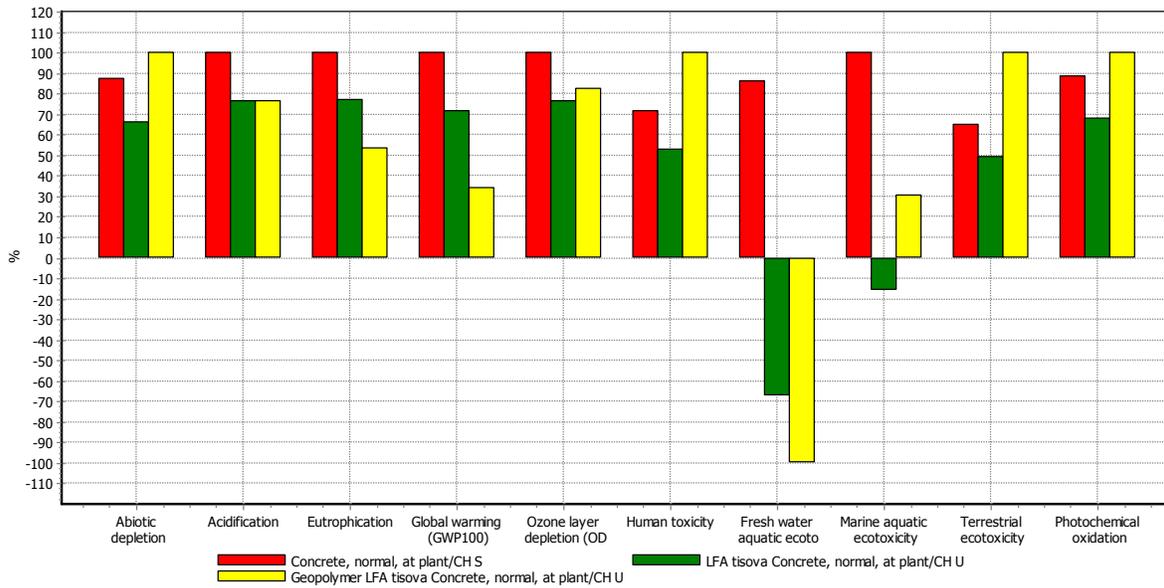
It should be researched if there are alkaline waste materials that potentially could be used to replace Ksil. This could further diminish the environmental impact of Geopolymers. Henk Nugteren is researching if a waste stream of the aluminum industry could serve this purpose.

8 Concrete comparison

The main goal of this research was to identify the environmental impact of 1 tonne of processed LFA. The difference analysis that was done provides an indication of the possible advantages of processing LFA into concrete. These results are useful to scientists, producers of LFA and the policy makers that create environmental policies. The most important actors that will determine if LFA will be processed in concrete are however the producer and user of concrete. The demand for LFA will depend on these actors. Therefore an environmental comparison based on 1m³ concrete is made, which was the second FU for this LCA (§Goal and scope3.4.1). To get an indication on the environmental performance of geopolymers, geopolymer-concrete is also compared with the other types of concrete. The concrete records for LFA-concrete and geopolymer-concrete have been created by adapting theecoinvent record for conventional concrete (*Concrete, normal, at plant/CH U*). Because geopolymer-concrete contains fluid, the Ksil an LCA comparison with the cement powder is hard to make. In order to compare the LCA results of geopolymer-concrete with the LCA results of conventional concrete and LFA-concrete, the cement paste in the conventional concrete record is replaced with geopolymer paste.

In the conventional concrete record, 300 kg cement and 186 kg water are used to produce 1m³ of concrete. In the LFA-concrete record, 30% of the cement (90kg) was replaced with Tisova LFA. By using it in concrete, the dumping of 90kg of Tisova LFA is prevented. These prevented emissions can be allocated to the concrete production and the lignite-fired power plants. Because the concrete production needs to make an effort to process it in their concrete, in this case the prevented emissions are allocated to the concrete.

In order to construct the geopolymer-concrete, a sub record of geopolymer paste which is based on the recipe in Table 22 had to be constructed. In this record all the ingredients of 1kg of Tisova geopolymer are incorporated. 486kg of this geopolymer paste replaces all cement and water in the geopolymer-concrete record. In both adapted records, the difference in transport distances for the various components of the binder paste is not considered. The results of the environmental comparison between the different types of concrete are presented in Figure 17.

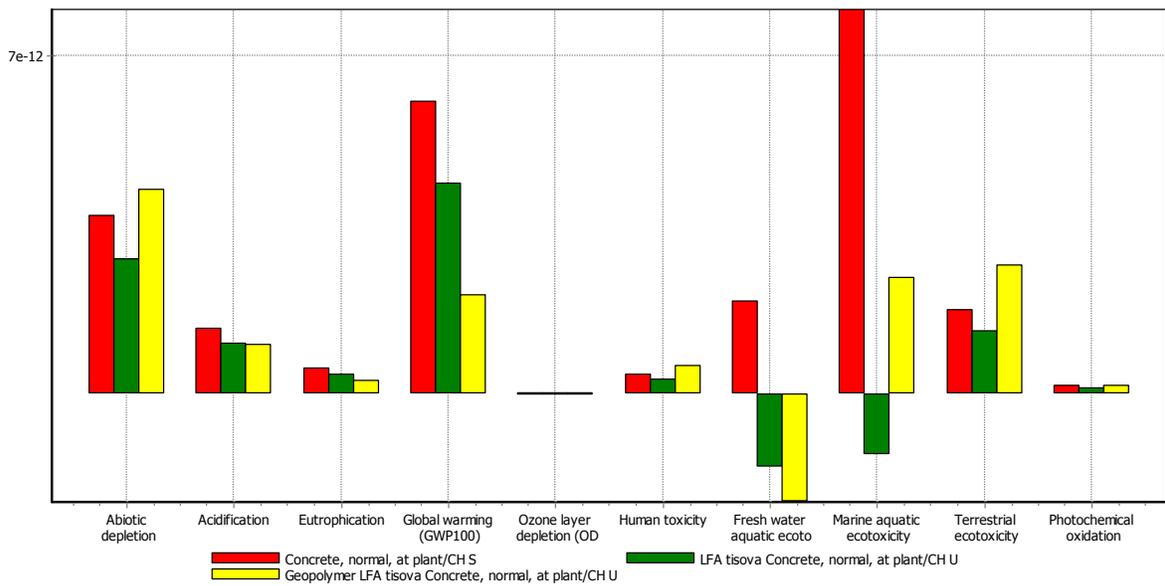


Comparing 1 m³ 'Concrete, normal, at plant/CH S', 1 m³ 'LFA tisova Concrete, normal, at plant/CH U' and 1 m³ 'Geopolymer LFA tisova Concrete, normal, at plant/CH U'; Method: CML 2 baseline 2000 V

FIGURE 17 ENVIRONMENTAL COMPARISON BETWEEN CONVENTIONAL CONCRETE, LFA-CONCRETE AND GEOPOLYMER-CONCRETE

Based on this comparison it seems that LFA-concrete performs better in terms of environmental impact, than conventional concrete in all categories. This could be expected because the additive of LFA only contributes with negative impacts due to the prevention of the dumping of LFA and prevention of production of cement. Because the dumping of LFA has no significant impact in global warming it can be concluded that the cement is the only significant contributor to global warming impacts of conventional concrete. Figure 17 shows that when 30% of the cement is replaced with LFA, the global warming impact decreases by 30%. The negative impact of dumping Tisova LFA originates from the fact that the impact of Tisova LFA-concrete is negative in Fresh water and Marine aquatic ecotoxicity. In the other ecotoxicity categories, the negative impact of dumping Tisova LFA doesn't exceed the impact of the other ingredients.

Geopolymer-concrete has the least environmental impacts in Eutrophication, Global warming and Fresh water aquatic ecotoxicity. In the toxic categories the production of Tisova geopolymer-concrete shows deviating image (Figure 17). The impacts on human toxicity are relatively high while the impacts on Fresh water aquatic ecotoxicity are the lowest.



Comparing 1 m³ 'Concrete, normal, at plant/CH S', 1 m³ 'LFA tisova Concrete, normal, at plant/CH U' and 1 m³ 'Geopolymer LFA tisova Concrete, normal, at plant/CH U'; Method: CML 2 baseline 2000 V.

FIGURE 18 NORMALIZED IMPACTS OF CONVENTIONAL CONCRETE, LFA-CONCRETE AND GEOPOLYMER-CONCRETE

When we assess the normalized impacts (Figure 18) of the normal concrete there are three categories that have the most significant contribution to the global emissions, respectively: Marine aquatic ecotoxicity, Global warming and Abiotic depletion.

As stated before, the Tisova LFA-concrete performs better in all categories compared to normal concrete. The other type of LFA-concrete will show a similar picture. Only in Fresh water aquatic ecotoxicity and Marine aquatic ecotoxicity, other types of LFA will show a deviating picture (Appendix 5).

Geopolymer concrete shows a relative high normalized score in Abiotic depletion and Terrestrial ecotoxicity. Especially the low impacts in Global warming are interesting. Based on the relative contribution and the amount of public attention, this remains the most important environmental category affected by concrete production. The low impacts in Global warming could provide an incentive to further develop this concept.

Depending on the type of reduction that is required, a specific concrete can be chosen. If Global warming would have the highest reduction priority geopolymer-concrete would be the best option. When Marine aquatic ecotoxicity impacts have the priority to be reduced, LFA- concrete would be the best of the three options.

9 Potential of LFA in concrete

Assessing the potential of LFA in concrete requires consideration of many different factors. This makes it very complex to make quantitative statements about this potential. Therefore only the factors and their relations that determine this potential will be addressed in this chapter.

9.1 Technical performance

LFA cannot be seen as a single product. It is a name for different types of fly ashes from lignite-fired power plants which all have different characteristics. Some show a significant strength development when applied in concrete, while others show hardly any reaction. The potential of this processing option is however strongly dependent on the technical performance. Based on the technical performance, the replacement potential can be assessed. Replacing only a few percent of cement with LFA will have little effect on the technical performance, but will also generate minimal economical and environmental benefits. It is unlikely that replacement of less than 10% of the cement forms enough incentive to change the conventional concrete production.

This research has shown that 5 out of the 6 samples that were tested achieved more than 90% of the reference compressive strength when replacing 15% of the cement by LFA. When 30 % is replaced, 3 out of the 6 samples achieved over 85% of the reference compressive strength.

The exact replacement potential depends on the specific LFA that is used and its particular application. In general, based on the performed tests 30% replacement seems to provide the optimum balance between economical and environmental advantages and a disadvantage of loss in technical performance.

In general LFA in comparison to cement shows a slower strength development. This could be problematic in applications that require high early strengths. Field research has shown that there are several application possibilities. Foundation and stabilization are already done with EON LFA. In these areas there will be an enormous potential to process LFA and replace cement. An example of a possible low-grade high-volume application would be the “Tweede Maasvlakte”. This is a new part of the Rotterdam harbor that is currently under construction. Most of its surface will be hardened and needs to be stabilized or founded. Dike reinforcement could be another area where LFA may prove to be a useful building material. New concepts, recipes and building methods will have to be developed to take advantage of the full potential of this material. Further development of the recipes could provide an optimal LFA use for each type of LFA.

In practice the LFAs that show the best performance will be the first ones used. The LFAs that show less strength development could be used in applications with lower strength requirements. The applications that were tested are limited. This research has focused on high-grade concrete that can be used for construction purposes. Large scale use of LFA in low-grade application seems however a more realistic option.

At this moment LFA appears to be an inferior by-product in comparison with HFA and GGBFS. When HFA and GGBFS are widely and cheaply available, the industry will probably prefer these by-products over LFA. If however HFA and GGBFS become scarcer and their price gets higher, LFA can become an economically attractive alternative.

9.2 Environmental performance

Although it is hard to quantify the environmental effects of depositing LFA, it seems clear that preventing depositing of LFA and preventing cement production has a significant environmental benefit. It can be seen that LFA-concrete performs better in all environmental impact categories in comparison with conventional concrete. Only the extra transport that would be required is an environmentally negative aspect of LFA-concrete. The contribution of this transport to the entire environmental profile is however relatively low.

There are other rest products like GGBFS and HFA that are already used to replace cement. In current LCA studies GGBFS and HFA are seen as waste product and so no emissions are allocated to the use of these materials. When these products are used in concrete construction they will also improve the environmental profile. The higher the percentage of cement that can be replaced by waste products, the better the environmental profile of the concrete will become.

GGBFS and HFA do however have a positive value and can be considered as by-products instead of waste products. Allocation of emissions to by-products can be done on an economic basis. This implies that a part of the emissions of the coal-fired electricity production and the steel production have to be allocated to respectively fly ash and GGBFS. The scarcer these by-products become, the higher their price will be. A higher price in turn leads to a larger share of the emissions when applying economic allocation. At this moment most LFAs do not have a positive value yet. If through more research some LFAs become more interesting to use as a raw material, the demand will increase. When certain LFAs become scarce they will also have a positive value and they become by-products instead of waste-products. If economic allocation is applied, the environmental profile of these LFAs will change as well. It is debatable when rest/waste products turn into by-products on which emissions have to be allocated. This discussion is already the case for HFA and GGBFS, and will be for LFA.

Regulation and taxing could play an important role in the selection of the processing option of rest materials. When stricter regulation on LFA dumping is enforced, other processing options might become more interesting. The same can be said for regulation of polluting of building material (cement) production. It will also favor the use of rest products in concrete.

The electricity production from lignite-fired power plants is one of the most polluting forms of electricity production. With the debate on climate change, this type of electricity generation is ever more under discussion. Due to the environmental effects of lignite electricity the long term future is uncertain.

9.3 Economical performance

If the processing of LFA in concrete is a realistic option depends both on the technical, environmental and economical performance. If LFA-concrete is economically unattractive, there will be no demand and processing in concrete will not occur.

The costs of LFAs will depend on their supply and demand. At this moment the supply exceeds the demand and the material is predominantly deposited. This implies that LFA has no real value because there is no scarcity (for the majority of LFAs). If anything, a negative value could be assumed, because the LFA needs to be processed in deposits.

The market for LFA will mainly be determined by the market of its competitors. The cement which costs range between 60 and 100€/tonne is the dominant force in the binder market. Energy prices strongly effect the price of cement. The other main competitors are GGBFS and HFA. They are more similar in technical and environmental performance. When HFA and GGBFS become scarcer and their price will get higher, LFA can become a good alternative. Whether or not a specific LFA will have a positive value depends on the relative performance to other by-products.

If dumping of by-products or the pollution caused by cement production was priced by tax measures from the European Union, using these by-products in concrete would get an extra incentive. This in turn would create scarcity in these by-products and their price would increase. At that moment the discussion in §9.2 becomes relevant: “a higher price in turn leads to a larger share of the emissions when applying economic allocation”. When these emissions are also priced by tax measures, they will decrease the market potential again. It would be interesting to see which measures would be the most effective in reducing environmental impacts. Because the environmental impacts are so hard to determine and the effects are complex, taxing of most emission seems unrealistic.

Transport costs play an important role in the cost price for rest products. Because the value of the rest products at the factory is low or even negative, the fraction of the transportation costs is relatively high. Whether or not LFA is economically interesting depends mainly on the transport costs. Transportation in trucks seems to be the most convenient method. LFA has to be transported in concealed silos to prevent dust forming through wind erosion. The transportation costs per tonne/km are hard to determine. They depend on the many factors (labour costs, fuel costs, maintenance costs) that change through time and place. Total distance and transshipment method are also determinative for the transportation costs per tonne/km. Roughly, transport costs in the region of 0.10 €/tonne/km can be assumed, which makes long transport distances economically unattractive. Although a transporting distance of 500km seems environmentally responsible, economically, such a distance will form a barrier.

9.4 Geopolymers

The market potential for geopolymers is even harder to assess than the potential for LFA-concrete. Geopolymers are still in an early stage of development, especially with LFA as a raw material. Still, first indicative tests show that with some types of LFA, geopolymers could be an interesting alternative. If the research on this material develops, it could prove applicable in several high strength applications.

The use of Ksil as an alkaline activator in the geopolymers does give some problems. Production of Ksil is relatively intensive and does emit a lot of CO₂. Furthermore, the production costs of Ksil are very high (in the region of 500€/tonne (PQ Europe)). Because in the production of concrete only about 1/5 of the weight of cement is needed in Ksil, the costs of 1m³ concrete roughly remains the same as conventional concrete (assuming a zero value for the rest materials used). As we have seen in Figure 17, the CO₂ impacts of geopolymer-concrete are lower than conventional and LFA-concrete. In some other impact categories though, like Marine aquatic ecotoxicity, the LFA-concrete performs better. Due to the use of primary materials and energy in the Ksil production process, the

impacts in some categories are relatively high. Preferably an alternative alkaline activator would be used in the geopolymers recipe. Perhaps there are other alkaline activators which have a less intensive production process while fulfilling the same function. Ideally a waste alkaline activator would be used. It would have both environmental and economical advantages if an industrial waste stream, that would otherwise have to be disposed, could be used in geopolymers.

9.5 Market acceptance

The building industry is a conventional sector which exhibits high resistance to entry of new products. This has the following reasons. The end-product that the building industry supplies, needs to have a guaranteed lifetime. If during this lifetime problems occur, the supplier will be held accountable. Therefore the building industry demands reliable products, with which they have sufficient experience. Because the different types of LFA have a different character, it is difficult to establish a stable reputation in the market. Furthermore the heterogeneity might provide problems overtime. The industry requires products with constant quality. If there are fluctuations in the quality of the LFA, the concrete construction could be at risk.

The production of LFA concrete requires an adaptation in the production process. Although the adaptations will be limited, it is not sure that the existing infrastructure is suitable to produce LFA-concrete. Furthermore, a different way of processing at the building site could be required. Other strength development could for instance change the demoulding process.

The market is not yet interested in the environmental profile of the products they supply. There is not enough (economical) incentive to provide sustainable products. The cement industry is globally dominated by a few players. This industry has a lot of power towards the building industry and the governments. In many norms and regulations the minimal use of cement is prescribed. This impedes the development of new materials.

At this moment the market will apply LFA in low-grade low-risk applications. These applications will have to have low constructive risks, limited human contact possibilities, no strict norms and low cost. Examples of these type of constructions are presented in §9.1. The market acceptance for geopolymers is still far away. Because of the nature of the processability, using geopolymers in the prefab industry would have the most perspective.

9.6 European situation

The European Union was chosen as the location scope of this research. The EU however isn't a uniform area. There are many local differences between the countries in the EU. LFA is produced in only a few countries which all have a different processing culture. Although the European Union has common environmental regulations, there are still many deviating practices among the Member States. Both implementation and enforcement is much stricter in some states than in others. As discussed before, European regulation and tax measures could increase the use of LFA.

Because the transport costs are an important factor in the economical potential of LFA-concrete, the production of LFA-concrete will probably be limited to LFA producing countries or nearby neighboring countries. This limits the market potential in Europe. When we compare the estimated annual LFA production of 40 million tonne, with the annual European cement production of around 300 million tonne, it is unlikely that all LFA could be used in cement replacing application.

If there is no natural market for LFA, it could be created by the EU or the respective governments. There are several instruments to do this:

1. Restrictive measures on pollution from cement production. When the cement production is restricted or taxed on the pollution it causes, the production costs will increase. Consequently other alternatives like LFA will become more interesting
2. Restrictive measures on dumping of LFA. When the dumping of LFA is restricted or taxed, the need for alternative processing options increases. Consequently processing LFA in concrete will become more interesting.
3. Stimulating research on alternative processing options. Because thus far there have not been enough incentives to process LFA in concrete, the knowledge and experience of using LFA in concrete recipes is limited. Therefore the full potential of this option is not yet developed. If the research on using LFA in concrete was stimulated, the market could get a better insight in the potential of this material. When the specific recipes, risks and advantages of LFA concrete would be better known, it could prove to be a viable option.

The application of LFA in concrete will be a gradual process in which the best performing types of LFA are used first. It will probably require a lot of time before the concrete market will adapt towards the applications of LFA. It could be that while the full market potential is being developed, the annual production LFA is declining. Although there is enough lignite available, and it will probably take a lot a time before lignite and LFA production is phased out, lignite production cannot go on forever. A trend towards more sustainable forms of electricity can be observed. Since electricity production from lignite is one of the most polluting forms of electricity generation, replacement of lignite has a priority (Kavouridis 2008). The general European interest can however conflict with national interests. Some European countries like Germany depend on lignite as their only national fossil energy resource. Because most countries want some independence in their energy production, lignite electricity will remain to play an important role until a proper alternative has been found.

If the European Union however would create a new environmental policy that restricts the pollution from lignite-fired power plants, the production of lignite electricity and thus LFA would also be restricted. On which timescale a serious effort will be made to phase out LFA will depend on politics.

10 Discussion

The present research was conducted within limits of feasibility. For future developments, a number of points for potential improvements can be identified.

First, The methods to determine the emissions caused by depositing can be improved. This could be done by taking into account more factors that influence the emissions of an LFA deposit and modeling these emissions. Such additional analysis however is practically very difficult because it requires development of a very extensive model for which many causal relations between different factors determining emissions are not even known. Moreover, the method that was used to determine the emissions represented the situation that the pH of the deposit becomes neutral. It is however not known what the long term pH development of LFA deposits will be. If through time the pH would decrease or increase, it could strongly affect the leaching behavior of the deposit.

If we would be able to model the emissions of LFA deposits correctly, it would still be complicated to determine the environmental effect of these emissions. The characterization that is used in the CML method is debatable. The different timescales that can be selected in the CML method have an effect on the characterization factors. When we only consider the effects of the emissions for 100 years, it has a different impact than if we consider the effects on a timescale of 60000 years. Some substances remain to have an impact on the environment for thousands of years, when all these effects are added, a very high cumulative impact is the result. The impact on this timescale (60000 years) is very hard to determine and the uncertainty of the effect will be high. No effect measurements that date more than 100 years back can be recorded. Discarding the long term effects of the emissions is however not a sustainable option, it could put an extra burden on future generations.

It was chosen to use the CML 2 baseline method with an infinite timescale because it is the default in the CML method. The impact categories in which emissions will continue to have environmental impacts have high characterized impact values when assuming an infinite timescale. In Marine aquatic ecotoxicity for instance, the characterized impact values are high because the toxic emissions remain in the seas (marine) and will continue to affect the sea-life. Due to the high uncertainty of these effects the value of this impact is hard to interpret.

Because there is no spatial and time element in the CML method used, the effects of concentrations cannot be determined. The concentration of harmful elements is however determinant on the effect it has on organisms. A short time, high dose concentration can be much more damaging than a long time low dose concentration. This especially plays an important role with the toxic emissions concerning dumping of LFA.

Both the long term leaching behavior of LFA deposits, as the long term effect of the emissions from LFA deposits seem highly uncertain. It is therefore hard to assess the value of the methods that were used. This is confirmed by the fact that changes in assumptions or methods can lead to enormous fluctuations of end result of the LCA. Interpreting the results and determining extend of the environmental impact of depositing is therefore not very useful. Sadly, because of the high uncertainty, no firm conclusion about the effects of depositing LFA could be drawn.

When the lignite isn't mined and burned in the lignite-fired power plant it will remain in the ground. All the material that is in the ashes originates from the lignite. This means that the material that is leached out of the LFA, originally would also be in the ground. It therefore is the question what the difference in leaching behaviour of this material is in LFA and natural lignite. In this study the natural leaching of the lignite has not been considered. Although it is assumed that LFA has a different leaching behaviour than lignite, the difference between these two leaching behaviours should be considered in order to assess the impacts of the lignite burning process. This difference can be calculated by subtracting the natural emission of lignite with the emissions of deposited LFA. If the mining of lignite however would prevent natural leaching emissions, these prevented emissions could be allocated towards the LFA in that way diminishing the LFAs impact. The prevented emissions could also be allocated towards the lignite-electricity production because LFA is considered a waste product and no emissions are allocated to the LFA. It would depend on the specific choices that are being made in the LCA modelling to which product this prevented emission would be allocated.

Several elements of application of LFA in concrete have been researched. The strength development tests were limited to only three different percentages of cement replacement. When LFA will be used in low-grade application the strength requirements would be low. If higher percentages of cement replacement would have been tested, the potential for this low-grade application could be assessed as well. The average value for the compressive strength was based on 6 measurements, the average value for the flexural strength test were based on 3 measurements. More measurements are needed to draw sound conclusions about the strength contribution of LFA. Furthermore these measurements were only done at two time intervals (28 and 90 days). If measurements before 28 days and after 90 days would have been done, judgments about early strength development and final strength could have been made.

Only one sample from each production location has been acquired. If other samples from the same production location had been acquired at another point in time of the production (for instance 1 month later), conclusions about the variation about the composition in time could have been drawn. A constant composition of the LFA is an important factor in determining the potential of processing LFA in concrete.

If a reference prisms which had 30% inert powder would have been constructed, conclusions about the chemical strength development of the LFA could have been drawn. This inert material would need to have the same grain-size distribution as the tested LFAs in order to rule out mechanical effects.

Not all factors that determine the applicability of LFA in concrete have been researched. Factors like heat of hydration, shrinkage, set time, creep, modulus of elasticity, and soundness, could be important in specific application areas, but have not been assessed in this research.

The scale of the annual LFA production is hard to assess. This is due to the fact that no figures on European or national level of LFA production have been found. The estimated annual production was based on the annual lignite production multiplied with the average ash content and the average fly ash/bottom ash ratio. Both the average ash content and the average fly ash/bottom ash ratio were derived from the specific LFAs that were researched. It is not known if this is representative for the European situation.

The environmental impacts of LFA-concrete in the use and disposal phase were discarded. This has been done based on the fact that other research showed that the emissions in the use phase of HFA-concrete aren't higher than those of conventional concrete. It is not known if this will be the same case for LFA-concrete. The emissions in the use phase of geopolymers are not known at all. LFA production has been accepted as a fact. Making the assumption that LFA is a waste product discarded the problems surrounding lignite-fired power plants. The production of electricity from lignite-fired power plants is in itself a very polluting process. The electricity production from lignite is the largest contributor to the CO₂ production of Germany. "Lignite currently covers about 12 percent of Germany's primary energy requirements, but it makes up over 20 percent of its CO₂ budget" (Michel 2009). When LFA would generate incomes for lignite-fired power plants, the entire business model of those lignite-fired power plants would become more interesting. If for that reason the polluting lignite-fired production would larger than without the beneficial use of LFA, the environmental advantages of using LFA could be diminished by the disadvantages of the larger lignite-fired production. When the LFA production generates income, economical allocation will have to be applied to determine what the environmental impacts of LFA production are.

11 Conclusion and recommendations

This research has shown that there is a significant difference between processing LFA in deposits and LFA-concrete. From an environmental perspective, processing LFA in LFA-concrete is the preferred option. Although the methods to determine the environmental impact of dumping seem inadequate at this moment, it is important to get an insight in the consequences of dumping LFA. This study has shown that dumping of LFA causes several types of toxic emissions. There is however a large difference between these emissions among different types of LFA.

In general we can conclude that large scale dumping of all types of LFA will certainly negatively affect the environment. Due to the high uncertainty in both the emissions of dumping LFA and the effects of these emissions it is hard to make a judgment about the extent of the adverse environmental effect. Therefore, until today decision makers do not have the correct information that could enable them to make adequate decisions on LFA processing practices. This problem occurs with most environmental problems. It is for instance still uncertain what the exact effects of greenhouse gasses are on the earth's climate. Still there seems to be a global consensus on the need to reduce greenhouse gas emissions. Supporters of the precautionary principle claim that not knowing the exact effects cannot be an excuse to continue current practice. And that when the effects of dumping LFA are uncertain, prevention always seems the best option. Others might claim that it is wasteful to undertake various drastic prevention measures without even knowing what effects can be expected. To end this discussion more knowledge about these specific environmental impacts should be generated. When no measures are taken to prevent adverse environmental impacts, irreversible damage can be the result. Therefore taking measures even when the environmental effects are not exactly clear is already current practice with some environmental problems.

This research has shown that prevention of dumping LFA through processing in concrete might be a technically viable option. Although the LFA-concrete developed less strength than the reference concrete, 5 out of the 6 samples that were tested, achieved over 90% of the reference compressive strength when replacing 15% of the cement with LFA. When LFA can be used to replace cement in concrete other advantages occur. It has been shown that the cement production causes various environmental impacts. Especially the impacts on global warming are relatively high. Using less cement will create both environmental and economic benefits.

There are other industrial by-products that already have been used in concrete. HFA and GGBFS have been processed in concrete since a few decades. Because it has been relatively easy to dispose LFA in nearby mines the need for alternative processing option was less apparent than with GGBFS and HFA. Therefore knowledge and experience on processing LFA as a building material is less thoroughly developed. Furthermore, due to geological differences the composition of the different LFA shows a much larger variety than those of GGBFA and HFA. The large variation in the composition of each type of LFA makes it hard to establish a transparent market for this product. There is no single or general use for the different types of LFA. For each type of LFA specific knowledge and recipes will have to be developed. This probably has been the main barrier for processing LFA in concrete.

In this research a distinction is made between C and F class fly ashes can be made. Based on results of strength tests it can be concluded that the F class LFAs have a relatively slower strength development. In the overall performance no significant difference between C and F class LFAs has been observed. The Tisova LFA, which was on the border of the C and F class, performed well in both the LFA-concrete strength test and in the geopolymers strength test. Based on these results it is hard to favor C or F class LFA for application in concrete. New more strictly defined categories of LFA composition have to be composed in order to create a better distinction between the different characteristics. This will help both producers and users of concrete products to get a better understanding of the functionality of the specific types of LFA.

Transportation doesn't have a significant impact on the environmental profile of processing LFA in concrete. It does however strongly affect the costs and therefore the economic potential of LFA. Processing LFA in geopolymers might be an interesting option. The results of the indicative tests with LFA geopolymers provide new leads for further research. Due to the chemical buildup of geopolymers it was expected that the F class would perform better. Test results however didn't prove this hypothesis. Some LFA geopolymers exceed the expectations by performing better in the strength tests than the reference cement. The testing has to be intensified and the recipes need to be adapted in order to assess the true potential of LFA geopolymers.

Which types of LFA are going to be processed in concrete depends on the demand of the market. Considering the fact that 95% of the produced LFA is dumped there seems to be no natural market for LFA. Economic incentives could be created by governments to support processing of LFA in concrete. Restricting dumping practices and pollution from primary building material production as well as stimulating research on LFA processing could be ways to do this.

When we would perceive LFA as an industrial by-product instead of industrial waste-streams, it could have significant environmental benefits.

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APPENDIX 1 CEMENT COMPOSITIONS EN 197-1

EN 197-1:2000

Table 1- The 27 products in the family of common cements

Main types	Notation of the 27 products (types of common cement)		Composition [proportion by mass ¹⁾]										Minor additional constituents	
			Main constituents											
			Clinker K	Blastfurnace slag S	Silica fume D ²⁾	Pozzolana		Fly ash		Burnt shale T	Limestone*			
natural P	calcined Q	siliceous V				calcareous W	L	LL						
CEM I	Portland cement	CEM I	95-100	-	-	-	-	-	-	-	-	-	-	0-5
	Portland-slag cement	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	-	0-5
		CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	-	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	-	0-5
CEM II	Portland-pozzolana cement	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	-	0-5
		CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	-	0-5
		CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	-	0-5
		CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	-	0-5
Portland-fly ash cement	CEM II/A-V	80-94	-	-	-	-	6-20	-	-	-	-	-	-	0-5
	CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	-	-	0-5
	CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	-	-	0-5
	CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	-	-	0-5
Portland-burnt shale cement	CEM II/A-T	80-94	-	-	-	-	-	-	6-20	-	-	-	-	0-5
	CEM II/B-T	65-79	-	-	-	-	-	-	21-35	-	-	-	-	0-5
Portland-limestone cement	CEM II/A-L	80-94	-	-	-	-	-	-	-	-	6-20	-	-	0-5
	CEM II/B-L	65-79	-	-	-	-	-	-	-	-	21-35	-	-	0-5
	CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	-	6-20	-	0-5
	CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	-	21-35	-	0-5
Portland-composite cement ³⁾	CEM II/A-M	80-94	<----- 6-20 ----->										0-5	
	CEM II/B-M	65-79	<----- 21-35 ----->										0-5	
CEM III	Blastfurnace cement	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	-	0-5
		CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	-	0-5
		CEM III/C	5-19	81-95	-	-	-	-	-	-	-	-	-	0-5
CEM IV	Pozzolanic cement ³⁾	CEM IV/A	65-89	-	<----- 11-35 ----->				-	-	-	-	0-5	
		CEM IV/B	45-64	-	<----- 36-55 ----->				-	-	-	-	0-5	
CEM V	Composite cement ³⁾	CEM V/A	40-64	18-30	-	<----- 18-30 ----->			-	-	-	-	0-5	
		CEM V/B	20-38	31-50	-	<----- 31-50 ----->			-	-	-	-	0-5	

1) The values in the table refer to the sum of the main and minor additional constituents. 2) The proportion of silica fume is limited to 10%.
 3) In Portland-composite cements CEM II/A-M and CEM II/B-M, in Pozzolanic cements CEM IV/A and CEM IV/B and in Composite cements CEM V/A and CEM V/B the main constituents besides clinker shall be declared by designation of the cement.
 * L : total organic carbon (TOC) shall not exceed 0.5% by mass; LL: TOC shall not exceed 0.20% by mass.

APPENDIX 2 TRANSFER COEFFICIENTS ECOINVENT

disposal, lignite ash, 0% water, to opencast refill	TK short-term (0-100a)	TK long term (0-60'000a)
	mean value	mean value
	kg emitted 0-100a/kg landfilled	kg emitted 0-60'000a/kg landfilled
H2O	100,000%	100,000%
O	0,038%	22,709%
H	0,038%	22,709%
C	0,271%	100,000%
S	26,918%	100,000%
N	18,883%	100,000%
P	0,094%	56,177%

B	0,784%	63,283%
Cl	57,055%	100,000%
Br	98,309%	100,000%
F	13,046%	100,000%
I	100,000%	100,000%
Ag	0,016%	100,000%
As	100,000%	100,000%
Ba	0,003%	100,000%
Cd	0,003%	100,000%
Co	0,072%	100,000%
Cr	15,082%	25,000%
Cu	0,016%	100,000%
Hg	0,020%	100,000%
Mn	0,003%	100,000%
Mo	100,000%	100,000%
Ni	0,152%	100,000%
Pb	0,002%	100,000%
Sb	38,566%	100,000%
Se	38,566%	100,000%
Sn	0,008%	100,000%
V	0,615%	54,400%
Zn	0,005%	100,000%
Be	0,152%	100,000%
Sc	28,261%	100,000%
Sr	0,152%	100,000%
Ti	0,124%	100,000%
Tl	0,152%	100,000%
W	38,566%	100,000%
Si	0,564%	71,872%
Fe	0,001%	66,828%
Ca	0,038%	100,000%
Al	0,124%	100,000%
K	56,429%	100,000%
Mg	0,048%	100,000%
Na	69,283%	100,000%

APPENDIX 3 LEACHING RESULT IN MG / KG WATER

PH V LS 2

SampleName	1	2	3	4	5	6
Fly Ash	EON Schkopau	LE3	Tisova	WE500	Popilek	Ptolemis
LS	ls2	ls2	ls2	ls2	ls2	ls2
pH	12,6	4,5	12,6	12,5	5,1	12,5

	ICP OES
	ICP MS
	Below detection
	Above detection

Al 167.078	69,05	0,060	0,25	53,53	0,770	0,25	mg/kg
As 189.042	0,0060	0,0001		0,0006	0,0250		
B 249.677	3,12	0,135	0,005	0,025	4,065	0,025	
Ba 455.404	0,08	0,39	0,365	0,11	0,075	0,505	
Be 313.042							
Ca 315.887	751,78	1388,780	6306,50	409,13	339,760	6911,38	
Cd 226.502							
Cl 136.345	6,845	28,605	43,035	14,485	10,3	146,635	
Co 230.786	0,1	0,0		0,0	0,2		
Cr 205.552	0,0	0,3		0,1	0,0		
Cu 324.754	1,6	0,0		0,0	0,2		
Fe 259.941	0,1	0,0		0,0	0,0		
K 766.491	29,165	35,535	35,95	84,725	51,45	45,92	
Li 670.780	5,06	13,815	9,51	0,32	7,26	0,31	
Mg 285.213	26,5	0,0		0,0	36,1		
Mn 257.611	5,50	0,080	0,00	0,00	1,220	0,03	
Mo 203.844	0,0	0,3		0,2	0,2		
Na 589.592	43,69	30,515	83,715	1,935	88,6	14,425	
Ni 231.604	0,9	0,1		0,0	1,1		
P 177.495	0,125	0,06	0,05	0,08	0,09	0,085	
Pb 220.353	0,0	0,0		0,0	0,0		
S 182.034	1153,68	475,990	2492,20	163,40	412,410	2514,28	
Sb 217.581	0,0	0,0		0,0	0,0		
Sc 335.373						0,00	
Se 196.090							
Si 251.612	11,04	0,145	0,135	4,475	7,635	0,18	
Sr 407.771	6,88	33,340	82,93	11,60	2,300	61,50	
Ti 334.187	0,0	0,0		0,0	0,0		
V 292.402	0,03	0,005	0,01	0,11	0,025	0,005	
Y 360.073							
Zn 202.548	1	0,01	0,01	0,005	1,125	0,015	
Zr 257.139							

 limit
 Not measured

PH V LS 10

SampleName	7,00	8,00	9,00	10,00	11,00	12,00
Fly Ash	EON Schkopau	LE3	Tisova	WE500	Popilek	Ptolemais
LS	ls10	ls10	ls10	ls10	ls10	ls10
pH	12,60	4,50	12,60	12,50	5,10	12,50
Al 167.078	30,75	0,08	0,25	0,05	0,90	0,05
As 189.042	0,00	0,00	0,00	0,00	0,01	0,00
B 249.677	0,62	0,06	0,00	0,01	0,78	0,01
Ba 455.404	0,14	0,49	0,28	0,53	0,08	0,54
Be 313.042						
Ca 315.887	120,23	1119,22	4660,95	1169,37	379,55	1134,25
Cd 226.502						
Cl 136.345	6,28	20,58	19,40	47,87	5,41	43,79

 ICP OES
 ICP MS
 Below detection
 Above detection limit
 Not measured

Co 230.786	0,03	0,00	0,00	0,00	0,04	0,00
Cr 205.552	0,00	0,19	0,08	1,36	0,00	1,41
Cu 324.754	0,62	0,00	0,00	0,00	0,03	0,00
Fe 259.941	0,08	0,00	0,01	0,00	0,00	0,00
K 766.491	6,14	7,75	5,14	11,29	10,71	11,03
Li 670.780	1,02	2,93	1,52	0,11	1,45	0,10
Mg 285.213	4,73	0,01	0,02	0,02	7,70	0,03
Mn 257.611	1,13	0,08	0,00	0,08	1,28	0,08
Mo 203.844	0,01	0,16	0,12	0,22	0,14	0,24
Na 589.592	8,99	6,48	11,49	3,77	19,44	3,82
Ni 231.604	0,19	0,05	0,04	0,06	0,21	0,06
P 177.495	0,09	0,07	0,08	0,09	0,06	0,07
Pb 220.353	0,00	0,00	0,00	0,00	0,00	0,00
S 182.034	228,10	186,87	1559,43	435,94	455,70	427,46
Sb 217.581	0,00	0,00	0,00	0,00	0,01	0,00
Sc 335.373	.	.	.	.	.	.
Se 196.090	.	.	.	.	.	.
Si 251.612	3,01	0,23	0,34	0,45	2,98	0,47
Sr 407.771	1,55	14,29	25,73	4,47	2,73	4,38
Ti 334.187	0,00	0,00	0,00	0,00	0,00	0,00
V 292.402	0,03	0,01	0,02	0,03	0,03	0,03
Y 360.073	.	.	.	.	.	.
Zn 202.548	0,20	0,01	0,01	0,01	0,18	0,01
Zr 257.139	.	.	.	.	.	.

PH 7 LS 10						
SampleName	13,00	14,00	15,00	16,00	17,00	18,00
Fly Ash	EON Schkopau	LE3	Tisova	WE500	Popilek	Ptolemais
LS	ls10	ls10	ls10	ls10	ls10	ls10
pH	7,00	7,00	7,00	7,00	4,00	7,00
Al 167.078	0,62	4,00	44,02	0,71	228,45	2,52
As 189.042	0,00	0,00	0,01	0,05	0,05	0,00
B 249.677	2,60	0,63	12,67	5,58	2,34	2,87
Ba 455.404	1,45	0,11	0,61	0,40	0,67	1,21
Be 313.042	.	.	.	.	.	.
Ca 315.887	10797,18	100,73	7514,49	4179,61	304,22	6920,87
Cd 226.502	.	.	.	.	.	.
Cl 136.345	82,80	2,69	70,37	45,15	16,56	92,77
Co 230.786	0,02	0,02	0,19	0,05	0,15	0,03
Cr 205.552	0,00	0,00	0,00	0,01	0,21	0,56
Cu 324.754	0,01	0,04	0,82	0,00	1,81	0,00
Fe 259.941	0,00	0,00	3,65	0,00	62,77	0,01
K 766.491	9,68	6,07	9,53	49,36	16,72	18,03
Li 670.780	1,76	0,96	2,69	1,01	1,55	0,33
Mg 285.213	979,33	4,70	106,21	68,86	34,94	739,68
Mn 257.611	23,89	0,85	3,01	1,92	1,59	0,79
Mo 203.844	0,05	0,09	0,06	0,08	0,07	0,22

ICP OES
ICP MS
Below detection
Above detection limit
Not measured

Na 589.592	6,49	29,38	42,22	7,41	26,49	9,03
Ni 231.604	0,54	0,13	0,44	0,30	0,49	0,95
P 177.495	0,04	0,08	0,08	0,13	0,37	0,07
Pb 220.353	0,00	0,00	0,00	0,00	0,01	0,00
S 182.034	293,64	226,55	314,65	323,26	82,45	281,11
Sb 217.581	0,01	0,00	0,00	0,00	0,00	0,01
Sc 335.373	.	.	.	.	0,04	.
Se 196.090	.	.	.	.	.	.
Si 251.612	1,13	1,55	72,70	16,00	229,24	5,55
Sr 407.771	38,64	1,25	9,76	11,49	2,69	7,96
Ti 334.187	0,00	0,00	0,00	0,00	0,00	0,00
V 292.402	0,00	0,05	0,47	0,16	4,94	0,03
Y 360.073	.	.	.	.	.	.
Zn 202.548	0,26	0,11	1,49	0,02	0,83	0,20
Zr 257.139	.	.	.	.	.	.

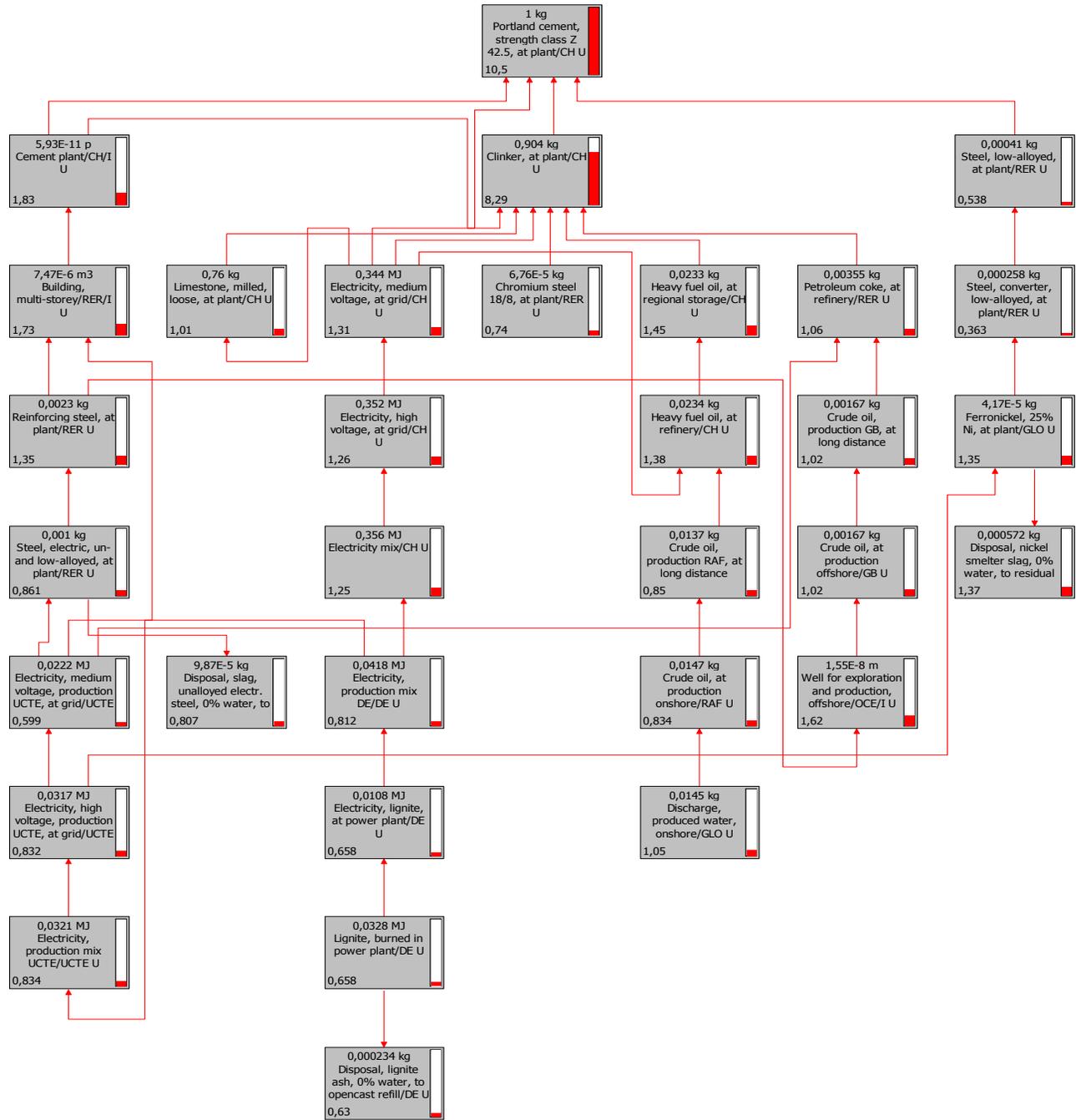
PH 4-12 LS 10

SampleName	19	20	21	22	23	24
Fly Ash	EON Schkopau	LE3	Tisova	WE500	Popilek	Ptolemais
LS	ls10	ls10	ls10	ls10	ls10	ls10
pH	4	12	4	4	12	4
Al 167.078	1048,260	70,18	441,480	41,210	100,98	5,26
As 189.042	0,2250	0,6990	0,3510	0,0020	0,4600	0,0020
B 249.677	13,595	0,73	14,135	6,87	0,965	2,965
Ba 455.404	2,355	0,04	0,635	0,58	0,11	1,89
Be 313.042	.	.	.	.	.	.
Ca 315.887	13860,040	72,03	7785,510	4838,260	208,43	11107,96
Cd 226.502	.	.	.	.	.	.
Cl 136.345	107,1	5,62	79,185	54,305	1,825	110,015
Co 230.786	0,5	0,0	0,2	0,1	0,0	0,3
Cr 205.552	0,5	0,0	0,3	0,0	0,0	0,0
Cu 324.754	0,1	0,0	2,4	0,2	0,0	0,0
Fe 259.941	788,9	0,1	21,3	5,4	0,0	0,3
K 766.491	10,4	5,195	14,815	72,795	9,975	33,19
Li 670.780	3,875	0,925	3,13	1,25	1,315	0,57
Mg 285.213	1188,0	0,1	129,9	99,6	0,0	1062,4
Mn 257.611	64,520	0,25	3,920	3,610	0,03	8,03
Mo 203.844	0,0	0,3	0,0	0,0	0,4	0,0
Na 589.592	10,045	173,035	67,455	11,115	223,92	14,525
Ni 231.604	3,6	0,0	0,5	0,4	0,0	3,7
P 177.495	0,9	0,155	1	0,09	0,08	0,09
Pb 220.353	0,1	0,0	0,0	0,0	0,0	0,0
S 182.034	352,110	242,08	388,700	256,040	452,85	257,77
Sb 217.581	0,0	0,0	0,0	0,0	0,0	0,0
Sc 335.373	0,02	.	.	.	.	.
Se 196.090	0,04	.	.	.	.	.
Si 251.612	264,35	14,555	235,18	79,285	5,325	50,795

ICP OES
ICP MS
Below detection
Above detection limit
Not measured

Sr 407.771	46,250	0,50	16,350	16,700	1,75	11,9
Ti 334.187	0,0	0,0	0,0	0,0	0,0	0,0
V 292.402	0,115	1,38	1,505	0,05	0,86	0,01
Y 360.073	-	-	-	-	-	-
Zn 202.548	2,12	0,005	1,67	1,85	0,01	1,505
Zr 257.139						

APPENDIX 4 CEMENT NETWORK MARINE AQUATIC DEPLETION



APPENDIX 5 SPECIFIED RESULTS OF PROCESSING THE VARIOUS TYPES OF LFA IN CONCRETE (1FU)

EON	Unit	Total 1FU	Truck 100 km	Dumping EON	Portland cement	Normalized Total 1FU
Impact category						
Abiotic depletion	kg Sb eq/1FU	-1,50E+00	8,96E-02	-1,12E-02	-1,58E+00	-9,46E-12
Acidification	kg SO2 eq/1FU	-1,12E+00	4,61E-02	-1,93E-02	-1,14E+00	-3,45E-12
Eutrophication	kg PO4-eq/1FU	-1,66E-01	8,58E-03	-3,24E-03	-1,71E-01	-1,25E-12
Global warming (GWP100)	kg CO2 eq/1FU	-8,25E+02	1,16E+01	-1,76E+00	-8,35E+02	-1,87E-11
Ozone layer depletion (ODP)	kg CFC-11 eq/1FU	-2,12E-05	1,84E-06	-1,22E-07	-2,29E-05	-1,86E-14
Human toxicity	kg 1,4-DB eq/1FU	-5,87E+01	3,28E+00	-1,70E+01	-4,50E+01	-9,81E-13
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	-2,47E+01	8,24E-01	-2,04E+01	-5,11E+00	-1,19E-11
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	-3,51E+04	1,23E+03	-2,58E+04	-1,05E+04	-4,63E-11
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	-1,18E+00	3,87E-02	-6,08E-03	-1,21E+00	-4,46E-12
Photochemical oxidation	kg C2H4/1FU	-4,23E-02	1,87E-03	-7,25E-04	-4,35E-02	-4,06E-13
LE3						
Impact category	Unit	Total 1FU	Truck 100 km	Dumping LE3	Portland cement	Normalized Total 1FU
Abiotic depletion	kg Sb eq/1FU	-1,49E+00	8,96E-02	-1,62E-03	-1,58E+00	-9,40E-12
Acidification	kg SO2 eq/1FU	-1,10E+00	4,61E-02	-1,67E-03	-1,14E+00	-3,40E-12
Eutrophication	kg PO4-eq/1FU	-1,65E-01	8,58E-03	-2,35E-03	-1,71E-01	-1,24E-12
Global warming (GWP100)	kg CO2 eq/1FU	-8,24E+02	1,16E+01	-2,22E-01	-8,35E+02	-1,87E-11
Ozone layer depletion (ODP)	kg CFC-11 eq/1FU	-2,12E-05	1,84E-06	-9,26E-08	-2,29E-05	-1,85E-14
Human toxicity	kg 1,4-DB eq/1FU	-4,98E+01	3,28E+00	-8,00E+00	-4,50E+01	-8,31E-13
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	-1,24E+01	8,24E-01	-8,11E+00	-5,11E+00	-5,99E-12
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	-1,85E+04	1,23E+03	-9,14E+03	-1,05E+04	-2,44E-11
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	-1,17E+00	3,87E-02	-8,49E-04	-1,21E+00	-4,44E-12
Photochemical oxidation	kg C2H4/1FU	-4,17E-02	1,87E-03	-7,01E-05	-4,35E-02	-4,00E-13
Tisova						
Impact category	Unit	Total 1FU	Truck 100 km	Dumping Tisova	Portland cement	Normalized Total 1FU
Abiotic depletion	kg Sb eq/1FU	-1,49E+00	8,96E-02	-9,24E-03	-1,58E+00	-9,45E-12
Acidification	kg SO2 eq/1FU	-1,11E+00	4,61E-02	-9,06E-03	-1,14E+00	-3,42E-12
Eutrophication	kg PO4-eq/1FU	-1,65E-01	8,58E-03	-2,68E-03	-1,71E-01	-1,24E-12
Global warming (GWP100)	kg CO2 eq/1FU	-8,25E+02	1,16E+01	-1,23E+00	-8,35E+02	-1,87E-11
Ozone layer depletion (ODP)	kg CFC-11 eq/1FU	-2,11E-05	1,84E-06	-1,94E-09	-2,29E-05	-1,85E-14
Human toxicity	kg 1,4-DB eq/1FU	-6,75E+01	3,28E+00	-2,58E+01	-4,50E+01	-1,13E-12
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	-7,84E+01	8,24E-01	-7,42E+01	-5,11E+00	-3,79E-11
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	-7,66E+04	1,23E+03	-6,73E+04	-1,05E+04	-1,01E-10
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	-1,17E+00	3,87E-02	-1,43E-03	-1,21E+00	-4,45E-12
Photochemical oxidation	kg C2H4/1FU	-4,20E-02	1,87E-03	-3,46E-04	-4,35E-02	-4,02E-13
Popilek						
Impact category	Unit	Total 1FU	Truck 100 km	Dumping Popilek	Portland cement	Normalized Total 1FU
Abiotic depletion	kg Sb eq/1FU	-1,49E+00	8,96E-02	-9,24E-03	-1,58E+00	-9,45E-12
Acidification	kg SO2 eq/1FU	-1,11E+00	4,61E-02	-9,06E-03	-1,14E+00	-3,42E-12
Eutrophication	kg PO4-eq/1FU	-1,74E-01	8,58E-03	-1,16E-02	-1,71E-01	-1,31E-12
Global warming (GWP100)	kg CO2 eq/1FU	-8,25E+02	1,16E+01	-1,23E+00	-8,35E+02	-1,87E-11
Ozone layer depletion (ODP)	kg CFC-11 eq/1FU	-2,11E-05	1,84E-06	-1,94E-09	-2,29E-05	-1,85E-14
Human toxicity	kg 1,4-DB eq/1FU	-2,08E+02	3,28E+00	-1,66E+02	-4,50E+01	-3,48E-12
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	-4,80E+02	8,24E-01	-4,75E+02	-5,11E+00	-2,32E-10
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	-4,55E+05	1,23E+03	-4,46E+05	-1,05E+04	-6,01E-10
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	-1,17E+00	3,87E-02	-1,43E-03	-1,21E+00	-4,45E-12
Photochemical oxidation	kg C2H4/1FU	-4,20E-02	1,87E-03	-3,46E-04	-4,35E-02	-4,02E-13
RWE						
Impact category	Unit	Total 1FU	Truck 100 km	Dumping	Portland	Normalized

Impact category				RWE	cement	<i>Total 1FU</i>
Abiotic depletion	kg Sb eq/1FU	-1,51E+00	8,96E-02	-2,69E-02	-1,58E+00	-9,56E-12
Acidification	kg SO2 eq/1FU	-1,11E+00	4,61E-02	-1,38E-02	-1,14E+00	-3,44E-12
Eutrophication	kg PO4-eq/1FU	-1,69E-01	8,58E-03	-6,40E-03	-1,71E-01	-1,27E-12
Global warming (GWP100)	kg CO2 eq/1FU	-8,27E+02	1,16E+01	-3,47E+00	-8,35E+02	-1,88E-11
Ozone layer depletion (ODP)	kg CFC-11 eq/1FU	-2,16E-05	1,84E-06	-5,51E-07	-2,29E-05	-1,89E-14
Human toxicity	kg 1,4-DB eq/1FU	-5,69E+01	3,28E+00	-1,51E+01	-4,50E+01	-9,50E-13
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	-3,34E+01	8,24E-01	-2,91E+01	-5,11E+00	-1,61E-11
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	-3,99E+04	1,23E+03	-3,06E+04	-1,05E+04	-5,27E-11
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	-1,18E+00	3,87E-02	-1,16E-02	-1,21E+00	-4,48E-12
Photochemical oxidation	kg C2H4/1FU	-4,22E-02	1,87E-03	-5,61E-04	-4,35E-02	-4,05E-13
Ptolemis	Unit			Dumping	Portland	<i>Normalized</i>
Impact category		Total 1FU	Truck 100 km	Ptolemis	cement	<i>Total 1FU</i>
Abiotic depletion	kg Sb eq/1FU	-1,49E+00	8,96E-02	-9,24E-03	-1,58E+00	-9,45E-12
Acidification	kg SO2 eq/1FU	-1,11E+00	4,61E-02	-9,06E-03	-1,14E+00	-3,42E-12
Eutrophication	kg PO4-eq/1FU	-1,65E-01	8,58E-03	-2,37E-03	-1,71E-01	-1,24E-12
Global warming (GWP100)	kg CO2 eq/1FU	-8,25E+02	1,16E+01	-1,23E+00	-8,35E+02	-1,87E-11
Ozone layer depletion (ODP)	kg CFC-11 eq/1FU	-2,11E-05	1,84E-06	-1,94E-09	-2,29E-05	-1,85E-14
Human toxicity	kg 1,4-DB eq/1FU	-6,44E+01	3,28E+00	-2,26E+01	-4,50E+01	-1,08E-12
Fresh water aquatic ecotox.	kg 1,4-DB eq/1FU	-3,98E+01	8,24E-01	-3,55E+01	-5,11E+00	-1,92E-11
Marine aquatic ecotoxicity	kg 1,4-DB eq/1FU	-4,64E+04	1,23E+03	-3,71E+04	-1,05E+04	-6,13E-11
Terrestrial ecotoxicity	kg 1,4-DB eq/1FU	-1,17E+00	3,87E-02	-1,43E-03	-1,21E+00	-4,45E-12
Photochemical oxidation	kg C2H4/1FU	-4,20E-02	1,87E-03	-3,46E-04	-4,35E-02	-4,02E-13