Available online at www.sciencedirect.com
ScienceDirect
Cement and Concrete Research 37 (2007) 781–788
Cement and Concrete Research

Comparative analysis of the life cycle impact assessment of available cement inventories in the EU ☆

Alejandro Josa [a,*], Antonio Aguado [a], Arnaldo Cardim [b], Ewan Byars [c]

[a] Technical University of Catalonia (UPC), School of Civil Engineering (ETSECCPB), C/Jordi Girona 1-3 Modul D2/C1, Barcelona 08034, Spain
[b] Civil Engineering Department, Polytechnic School of Penambuco University, Rua Benfica, 455-Madalena, CEP 50.750-410, Brazil
[c] Centre for Cement and Concrete, Department of Civil and Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK

Received 3 May 2005; accepted 12 February 2007

Abstract

Life cycle impact assessment (LCIA) is one of basic steps in life cycle assessment methodology (LCA). This paper presents a comparative study of the LCIA of different life cycle inventories (LCI) for EU cements. The analysis unit used is the manufacture of 1 kg of cement, from "cradle to gate". The impact categories considered are those resulting from the manufacture of cement and include greenhouse effects, acidification, eutrophication and summer and winter smog, amongst others.

The results of the study highlighted some inconsistencies in existing inventories. As for the LCIA, the main environmental interventions related to cement manufacture were classified and characterised and their effect on different impact categories analysed. Differences observed in evaluation of the impact of cement type were essentially related to their clinker content.

Keywords: Life cycle impact assessment; Life cycle assessment; Life cycle inventory; Cement production; System boundary; Clinker

1. Introduction

Life cycle assessment (LCA) methodology is used to evaluate the impact of processes or products on the environment [1]. The inclusion of every stage of the process or product's life cycle is fundamental to this analysis. In the case of products, every stage from the production of the raw materials to the end of their useful lives and their use and maintenance should be included. Thus, all significant environment impacts in their life cycle can be addressed.

In some cases, however, a full life cycle (cradle to grave) analysis is impossible and the analysis must terminate at an intermediate stage (cradle to gate) or begin and end at intermediate stages (gate to gate). This is the case, for example, when one analyses cement production, which has multiple specific applications (beams, pillars, pavements, bridges, etc.) and therefore disallows a unique life cycle to be defined (cradle to gate).

This type of partial analysis (not cradle to grave) is useful for evaluating possible improvements in environmental behaviour, as well as for constructing more complete life cycles for specific cement end-products (beams, columns, pavements, etc).

One of the fundamental parts of a LCA is the undertaking of a life cycle inventory (LCI), in which the energy and materials used and wastes emitted during the manufacture of a product are identified and quantified (in solid, liquid or gas form). This typically yields a long list of environmental interventions that is difficult to manage and interpret [1–5].

These environmental interventions in the inventory are classified and characterised during the life cycle impact assessment (LCIA) stage. During this process, the results are summarised into a short list of impact categories. These impact categories (such as the greenhouse effect or acidification), are much easier to interpret than the environmental interventions themselves.

An earlier paper [6] compiled and analysed LCI for EU cements and included both input and output data. The latter focused on main emissions resulting from the production of cement (CO_2, SO_2, NO_x and dust). Alternative techniques were

☆ This paper is dedicated to Ewan Byers, who died last year.

* Corresponding author.
E-mail address: alejandro.josa@upc.edu (A. Josa).

0008-8846/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2007.02.004

used to evaluate these emissions and thus check the results from different LCI and confirm the validity of the methodology.

Key issues in available LCI were summarised in the previous paper by the authors [6], such as a) the identification of some inconsistencies in the figures included in some of them, b) the possibility of using theoretical models to estimate some environmental interventions, c) that emissions are primarily produced during the production of clinker, and d) that the types of cement that require the least amount of energy for their production are those which use greater proportions of different types of additives.

The main objective of this paper is to undertake a comparative study of the impact assessment of the same LCI analysed in [6]; to check whether the inconsistencies described in [6] can also be identified in this case; and to confirm the necessity to have reliable and good quality LCI for cements in order to conduct LCA exercises of cement based products (concrete, buildings, etc.). The analysis unit used was 1 kg of Portland cement, with or without certain types of additives. These LCI were obtained from references [7,8] and from information provided by several manufacturers. Table 1 shows some basic information about the corresponding cements (name, reference [9–17], type, percentage of clinker and origin). Reference [6] provides some further information on the source data. It should be noted that the figures included in these inventories depend, among other things, on the system boundaries utilised in each case. Unfortunately the system boundaries are frequently described without enough detail in the corresponding references as stated in [6].

Table 1
LCI utilised in this paper ([6])

Original cement name and reference	Classification		Clinker (%)	Origin
Cement Portland I [7]	Type I	Portland cement	95–100	Holland
Cement Portland [7]	Type II/A-S	Portland slag cement	80–94	Holland
Blastfurnace slag cement [7]	Type III/B	Blastfurnace cement	20–34	Holland
Cement Hoogoven I [7]	Type III/B	Blastfurnace cement	20–34	Holland
Portland ash cement [7]	Type IV/B	Pozzolanic cement	45–64	Holland
Cement CH [7,9]	Type I	Portland cement	95–100	Switzerland
Cement N [8,(10)]	Type I	Portland cement	95–100	Sweden
Portlandcement NL1 [8,11]	Type I	Portland cement	95–100	Holland
Cement S [8,12]	Type I	Portland cement	95–100	Sweden
Cement SF1 [8,13]	Type I	Portland cement	95–100	Finland
Cement SF2 [8,14]	Type I	Portland cement	95–100	Nordic Countries
Portlandcement A [8,15]	Type II/A-S	Portland slag cement	80–94	Austria
Portlandcement NL2 [8,16]	Type II/A-S	Portland slag cement	80–94	Holland
Portlandcement NL3 [8,17]	Type II/B-S	Portland slag cement	65–79	Holland
Blastfurnace slag cement NL1 [8,16]	Type III/B	Blastfurnace cement	20–34	Holland
Blastfurnace slag cement NL2 [8,17]	Type III/B	Blastfurnace cement	20–34	Holland

LCA can be undertaken by following a number of different specific methodologies [18–21] which can use different impact categories such as greenhouse effect, stratospheric ozone depletion, acidification, eutrophication or toxicity, as well as have different hypotheses for evaluating their environmental impact. This paper uses the CML 1992 methodology ([18]) through a commercial software [22], which was one of the most widely used and accepted methodologies in Europe when the research project conducted was started.

CML 1992 is based on a method published by the Centre for Environmental Studies of the University of Leiden in 1992 and is a problem-oriented method [22]. The impacts considered are grouped into three broad categories: exhaustion of raw materials and energy (abiotic and biotic resource depletion), pollution (enhancement of the greenhouse effect, depletion of the ozone layer, human toxicity, ecotoxicity, or acidification, among others) and damage [18]. The method is a midpoint model which means that it is based on traditional LCIA characterisation and normalisation methods as indicators located between inventory interventions and endpoint effects and damages [19,23–28]. Midpoint analyses [25–27] reduce the amount of assumptions and the complexity of the modelling and results in comparison with endpoint analyses [19,28]. However, they make the interpretation of absolute results more difficult since they do not refer directly to the damages produced.

2. Impact assessment

The LCIA is also a fundamental stage in a LCA [1] and consists of a number of parts. In the first or classification part, each environmental intervention in the LCI is associated with the impact category or categories in which it has an effect (for example, CO_2 is associated with the greenhouse effect).

In the second or characterisation part, the relative effects of all the environmental interventions associated with each of the different impact categories are compared to one another (for example, 1 kg of CH_4 has the same impact on the greenhouse effect as do 11 kg of CO_2). A reference unit is defined for each impact category (for example, equivalent CO_2 on the greenhouse effect) as well as the corresponding characterisation factors (11, as indicated in the case of CH_4). Additionally, there may be a later phase of normalisation, in which the results of each impact category are divided by a reference figure (for example, for the greenhouse effect, worldwide CO_2 emissions is sometimes used) and a final weighing, which is based on socio-political preferences and leads to a unique score as result. CML 1992 includes a normalisation step based on both Dutch and European references and does not include a weighing step. Since it is based on a midpoint model, it does not assess the damage produced.

Of all the impact categories considered in the 1992 CML methodology ([18]), those that are affected by one or more of the main emissions resulting from the production of cement were the first to be analysed. In agreement with [6], these emissions are stipulated as CO_2, SO_2, NO_x and dust, which in Table 2 are presented in association with the corresponding

Table 2
Initial impact categories considered in the analysis

Impact area	Impact category	Airborne emissions of the system			
		CO_2	SO_2	NO_x	Dust
Global	Greenhouse effect	1			
Regional	Acidification		1	0.7	
	Eutrophication			1	
Local	Winter smog		1		1

impact categories. Table 2 also includes the corresponding characterisation factors of these environmental interventions.

The impact categories are classified as global, regional or local, depending on their geographical area of impact. This sort of classification facilitates a subsequent analysis of the results and decision-making depending on the scope of the point of view adopted.

3. Study of the global environmental impacts

3.1. Greenhouse effect

Table 3 shows the results of the greenhouse effect characterisation of the different types of cement studied. The values are expressed in grams of equivalent CO_2 per kg of cement produced. The relevant gas emissions related to the greenhouse effect in the LCI analysed are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which have the corresponding characterisation factors of 1, 11 and 270 respectively. However, the total influence of methane (CH_4) and nitrous oxide (N_2O) on the greenhouse effect is very small in comparison to the contribution of carbon dioxide (CO_2), which lies between 98.8% and 100%. This is because, despite having a lower characterisation factor (1), the amount of CO_2 emitted is much higher than the other gases. For this reason, only the values corresponding to this gas are included in Table 3.

It is important to acknowledge the substantial quantitative effects of CO_2 emissions. Depending on the type of cement, these can reach values as high as 800 g of CO_2 per kg of Type I cement. This data supports the opinion of the Intergovernmental Panel on Climatic Change [29], which states, as it is currently widely known, that the production of cement is a relevant industrial source of CO_2 emissions.

The variations shown between the emission values of different cements in Table 3 are due mainly to the amount of clinker in the cements, since it is highly likely that the environmental interventions coming from the additions are considered nil in all cases. The variations in total CO_2 are also related to the type of resources utilised (mainly the fuels).

Despite the fact that Type I cements typically have a CO_2 emission of 800 g per kg of cement, quoted figures can be as low as 354.70 g per kg, as shown for the Cement Portland I [7]. The variation may be due to the fact that, for Cement Portland I, some of the emissions caused by the production of clinker are being omitted (perhaps only those associated with the fuel are considered), either because a certain proportion of these emissions are for some reason omitted from the inventory, or due to variations in definition of the system boundaries. This is confirmed by the fact (as is shown in [30]) that The Netherlands, the country of origin of this cement, has only one furnace producing clinker and three plants producing cement, all of which should yield very similar results (compare Cement Portland I with Portland Cement NL1 [8,16]).

The principal source of variation in the results for the remaining types of cements is the amount of clinker in each. The

Table 3
Characterisation of the cements studied with respect to greenhouse effect (in grams of equivalent CO_2 per kg of cement), acidification (in grams of equivalent SO_2 per kg of cement), eutrophication (in milligrams of equivalent PO_4 per kg of cement), and winter smog (in g of equivalent SPM per kg of cement)

Type	Cements	Global impact		Regional impact					Local impact		
		Greenhouse effect		Acidification			Eutrophication		Winter smog		
		CO_2	Total	SO_2	NO_x	Total	NO_x	Total	Dust	SO_2	Total
I	Cement Portland I	355	355	0.43	0.67	1.10 [b]	124	124	10.0	0.4	10.4 [d]
	Cement CH	810	810	0.60	1.40	2.00	260	260	0.3	0.6	0.9
	Cement N	813	817 [a]	0.67	1.46	2.13 [b]	272	272 [c]	0.2	0.7	0.9
	Portlandcement NL1	853	853	0.08	1.81	1.89	335	335	7.5	0.1	7.6
	Cement S	805	808 [a]	0.45	1.36	1.81	252	252	0.2	0.5	0.6
	Cement SF1	780	788 [a]	0.63	2.59	3.22	481	481 [c]	0.4	0.6	1.0
	Cement SF2	813	823 [a]	1.33	2.07	3.40	384	384 [c]	0.3	1.3	1.7
II	Cement Portland	918	920 [a]	1.16	2.17	3.33 [b]	403	403 [c]	0.2	1.2	1.4
	Portlandcement A	586	586	0.12	1.10	1.22	204	204	0.2	0.1	0.3
	Portlandcement NL2	807	807	0.09	2.07	2.16	384	384	0.2	0.1	0.3
	Portlandcement NL3	289	289	0.98	0.49	1.47	92	92	79.6	1.0	80.6
III	Cement Hoogoven I	222	222	0.51	0.35	0.86 [b]	66	66	10.0	0.5	10.5 [d]
	Blast furnace slag cement	334	338 [a]	0.58	0.77	1.35 [b]	142	143 [c]	0.1	0.6	0.7
	Blastfurnace slag cement NL1	212	212	0.03	0.60	0.63	111	111	0.1	0.0	0.2
	Blastfurnace slag cement NL2	134	134	0.43	0.28	0.71	52	52	88.6	0.4	89.0
IV	Cement Portlandash	693	695 [a]	0.90	1.63	2.53 [b]	302	302 [c]	0.2	0.9	1.1

[a] Includes minor contributions from CH_4, N_2O or HF.
[b] Includes minor contributions from HCl and NH_3.
[c] Includes minor contributions from NH_3, N-tot and COD.
[d] Includes minor contributions from soot.

Table 4
Characterisation factors used for acidification and eutrophication

Emission	Acidification	Eutrophication
NH_3 (ammonia)	1.88	0.33
HF (fluorhydric acid)	1.60	–
HCl (hydrochloric acid)	0.88	–
NO_2 or NO_x (nitrogen oxides)	0.70	0.13
SO_2 or SO_x (sulfur dioxide)	1.00	–

inconsistencies in some of the results have already been analysed in [6] and are due to several factors, including the definition of system boundaries and numerical errors. In cement types that incorporate high percentages of pozzolanic or cementitious additions (such as blast furnace slag or fly ashes), for example, Type III cements, the CO_2 emission reductions can be significant compared to corresponding Type I cements.

3.2. Other sources of global environmental impact

As for other sources of global environmental impact (such as the contribution to the stratospheric ozone depletion), the production of cement does not have a significant effect, as can be observed in different cradle to grave analysis of specific applications [31,32].

4. Study of the regional environmental impact

Some of the emissions caused by the production of cement have regional effects, such as acidification and eutrophication. As shown in Table 2, the main emissions resulting from the production of cement that contribute to these processes are sulfur dioxide (SO_2) and nitrogen oxides (NO_x). However, as these are among the environmental interventions in the inventories, other influential emissions have also been included in this study, such as hydrochloric acid (HCl), ammonia (NH_3), total nitrogen (N-tot) and the chemical oxygen demand (COD), which come from the energy production, though their effect is almost negligible and, for this reason, the detail of their effect has not been included in Table 3.

Characterisation factors are taken from Table 4 [18]. The reference units are the equivalent sulfur dioxide (SO_2) for acidification and the equivalent phosphatic compound (PO_4) for eutrophication. Both of these impact categories are analysed in the following sections.

4.1. Acidification

The main results that correspond to this impact category (in reference units) for all the cements studied are shown in Table 3. The main emissions of SO_2 and NO_x during the production of cement occur during the high-energy combustion of fossil fuels used to produce clinker and those used by mechanical equipment and vehicular transport. However, SO_2 emissions also occur when clays are used as raw materials in the production of clinker and the fraction of SO_2 not chemically combined is emitted into the atmosphere.

The total emission (in g of equivalent SO_2 per kg of cement) depends on the type of cement and ranges between 1.1 and 3.4 for Type I, with an average of 2.2, between 1.2 and 3.3 for Type II, with an average of 2.0, and between 0.6 and 2.5, for Types III and IV, with an average of 1.2. These results are logical in light of their high dependence on clinker content.

Since a midpoint model is being used, it is difficult to assess whether these figures are high or low without comparing alternatives in gate to gate, cradle to gate or cradle to grave exercises. However, with some assumptions, it is possible to compare them with typical emissions of cement plants [33] or emission limits [34,35].

Assuming that the kiln exhaust gas volume, expressed as m^3/tonne of clinker (dry gas, 101.3 kPa, 273 K), is between 1700 and 2500, which applies to all types of kilns [33] and taking an average figure of 2000 m^3/tonne of clinker, the emissions for European cement kilns (gate to gate) range from less of 0.4 to 6 kg of NO_x (as NO_2) per tonne of clinker, with an average of about 2 kg of NO_x (as NO_2) per tonne of clinker, and from less than 0.02 to 7 kg of SO_2 per tonne of clinker. Taking into account the corresponding characterisation factors (0.7 for nitrogen oxides and 1.0 for sulfur dioxide), these figures are in line with those of Table 3 (in fact, the figures of Table 3 are in general below the mid point of the ranges given), though the former correspond to a gate to gate approach (less life cycle stages considered) and the latter to a cradle to gate approach (more life cycle stages considered). In relation to emission limits [34,35], they range from 500 to 1200 mg/m^3 for NO_x (about 1 to 2.4 kg per tonne of clinker) and from 50 to 600 mg/m^3 for SO_2 (about 0.1 to 1.2 kg per tonne of clinker) which are similar to the previous figures.

In Table 3, one can see the high proportion of total acidification that is typically caused by NO_x emissions (in g of equivalent SO_2) which result from using fossil fuels in the clinker furnace, machinery and vehicles. The contributions of HCl and NH_3 emissions, which are only included in some inventories, are practically negligible. The inclusion of the latter two environmental interventions in some inventories and not in others can be due to the fact that they were only deemed to be significant in some of the studies, or because different criteria were used to define their system boundaries. This last possibility would be another example of the heterogeneity of existing inventories.

4.2. Eutrophication

Eutrophication is a consequence of, among other things, the emission of nitrogen oxides (NO_x), which produces an enrichment of nutrients in aquatic reserves and agricultural soils. During the manufacture of clinker and cement, nitrogen oxides (NO_x) are emitted, the origin of which lies primarily in the type of fuel used in obtaining the clinker and in the production of electrical energy ([6]). There are other relevant emissions in the system being studied, such as ammonia (NH_3), total nitrogen (N-tot) and the chemical oxygen demand (COD), but their effect in the inventories studied is negligible in comparison with the effect of NO_x. Table 3 shows the results for the characterisation (in mg of equivalent PO_4 per kg of cement).

The results in Table 3, as expected, depend on the type of cement and furthermore, on the type of clinker. Thus, for Type I cement, the results for the characterisation ranged between 125 and 480 mg of equivalent PO_4, with an average of 300, whilst for Type II, they ranged between 90 and 400, with an average of 270, and for Type III, they ranged between 50 and 140, with an average of 90.

The observed differences among cements of a similar Type are considered to be due to errors in the environmental interventions or to the manner in which the inventories defined their system boundaries, as stated in [6]. For example, in the case of Cement Portland I, which has a lower than average equivalent PO_4 (124 mg), possible mistakes were detected in its inventory, as mentioned earlier. Thus, the inventory probably omitted a considerable amount of the NO_x emitted in the cradle to gate analysis of this cement.

These results suggest that a cement plant producing 1 million tonnes of cement a year releases 0.5 kg of phosphorus per hectare (assuming an influence distance of about 35 km – 20 miles – surrounding the cement plant). This figure is in line with the values set by the European Environment Agency for the industrialised countries of Western Europe in 1988–1996 [36]: an average of 2.8 kg of phosphorus per hectare for a population density of 240 inhabitants/km^2, from which almost 0.5 kg comes from industrial activities.

5. Local impact

Dust in the air can cause respiratory problems in humans, livestock and wildlife. These effects are included in the impact category referred to as winter smog which is one consequence of particulate air pollution by SO_2, dust and soot (the by-products of combustion).

Table 3 shows the main results corresponding to this impact category for each of the cements studied. This shows the effects of the main individual emissions (in g of equivalent suspended particle matter – SPM – per kg of cement), as well as the total effect. A characterisation factor 1 was adopted for all emissions. Soot is also included in some inventories but it has a negligible influence in all of them. For this reason it has not been included in Table 3.

Table 3 shows a very high variation in the inventoried results for SO_2 and, very particularly, for dust. Considering absolute values, it should be noted that the figures for Cement Portland I, Portlandcement NL1, Portlandcement NL3, Cement Hoogoven I and Blast furnace slag cement NL2 were two orders of magnitude higher than those of the other cements (0.25–1.50 g equivalent SPM per kg of cement). These results could be due to (a) errors in the inventories, in which case further emphasis is placed on the need to standardise inventory methodology, to (b) the effect of some initial stages of the life cycle analysed (for instance energy production) or to (c) the possibility that inappropriate dust filters were used at the production plant. The latter seems highly unlikely, due to the acute environmental sensitivity of the countries from which these cements came.

In analysing inventories for life cycle stages previous to the cement factory gate and taking into account the strict particle emission limits in force in the countries from which the cement inventories come (20 to 50 mg/Nm^3, about 0.04 to 0.1 kg per tonne of clinker) it seems clear that the high figures and variation observed should come from the mining and preparation of energy resources. Since local impacts are being considered, the corresponding effects in each stage of the life cycle specifically affect the area where the activity is done.

Table 5
Characterisation factors for other emissions that affect the impact categories of photochemical ozone formation, heavy metals and carcinogens

Emission	Ozone formation	Heavy metals	Carcinogens
Aldehydes	0.443	–	–
Arsenic	–	–	0.044
Benzene	0.189	–	0.00044
Benzo(*a*)pyrene	–	–	1.0
Cd (cadmium)	–	50	–
Cr (chromium)	–	0.2	–
CH_4 (methane)	0.007	–	–
C_xH_y	0.398	–	–
Ethylbenzene	–	–	0.000044
Phenol	0.761	–	–
Fluoroethane	–	–	1.0
Hg	–	1.0	–
Ni	–	–	0.0044
PAHs	0.761	–	1.0
Pb	–	1.0	–
VOC	0.398	–	–

6. Other characterised environmental impacts stemming from minor emissions

The results shown in [6] demonstrate the existence of other emissions that, though of a lesser magnitude, may have a significant effect on some impact categories. This section examines some of these that have both regional implications, such as the photochemical ozone formation (summer smog), and local implications, such as heavy metals or carcinogens with toxicity effects. These have been characterised using the factors in Table 5.

It is important to note that these emissions stem mainly from energy-producing processes, in particular electricity production and the refining of primary fuels (petroleum, coal, etc.). Despite the environmental effects that these entail within the system boundaries of cement manufacture (cradle to gate), they generally affect areas that are not local to the cement plant.

The reference units for these impact categories are equivalent ethylene (C_2H_4) for the photochemical ozone formation (summer smog), equivalent benzo(*a*)pyrene (B(*a*)P) for carcinogens and equivalent lead (Pb) for heavy metals.

6.1. Photochemical ozone formation

The photochemical ozone formation (summer smog) depends on the presence in the troposphere of oxidizing photochemical substances, such as volatile organic compounds (VOCs) and carbon monoxide (CO). The effect of solar radiation on these substances gives rise to reactions between the oxidizing photochemical compounds and hydroxyl radicals (OH^-), in

the presence of NO_x, resulting in the formation of tropospheric ozone (O_3).

Table 6 shows the results of these impacts, measured in mg of equivalent C_2H_4 per kg of cement. The results are highly scattered, and a correlation with the cement type or definition of representative values is impossible. This fact can again be attributed, at least in part, to the criteria utilised or to the definition of the system boundaries in each case. However, it could also depend, in a decisive way, on the fuels utilised in the manufacture of clinker, some of which may lead to these sorts of emissions.

It can be seen in Table 6 that the inventories of certain cements do not include information corresponding to ozone formation (summer smog), which again calls into question the rigour with which some of the existing inventories were designed. Furthermore, Cement SF1 (367 mg of equivalent C_2H_4 per kg of cement) and Cement blast furnace slag (364 mg of equivalent C_2H_4 per kg of cement) have values an order of magnitude higher than the rest and it is impossible to define representative values for the cements studied. The best explanation for the degree of variation shown is that the results considered in Table 6 are highly dependent on the energy sources of the system and additional information on the processes that supplied power to the cement production system is needed.

6.2. Heavy metals and carcinogens

Any metal whose specific weight is higher than that of titanium (4.51 g/cm^3) is considered to be a heavy metal. These are found in small quantities in raw materials such as crude oil, rock and coal. As not all the heavy metals necessarily have adverse effects on health and not all of the harmful ones have the same implications, one must use characterisation factors to analyse their effect (Table 5).

Based on the inventories used, it can be assumed that these emissions mainly originate from the energy-producing systems, as there is no evidence that they are included in the raw materials used to make cement. The highly scattered results (very different orders of magnitude) make it impossible to assign a representative value to the cement (independent of its type), since such a value depends on the type of fuels utilised, both in the energy production and in the clinker furnace.

The results for Cement CH (4.01 mg of equivalent Pb per kg of cement) are surprisingly high. This result is either an undetected error inherent to the inventory, or the consequence of using fuels with extremely high contents of heavy metals.

As for the carcinogens, the same general comments can be made as for the heavy metals in terms of the origin of the emissions. As these results are significantly scattered and vary by orders of magnitude it is impossible to define representative values.

Table 6
Characterisation of the cements studied with respect to ozone formation (in milligrams of equivalent C_2H_4 per kg of cement), carcinogens (in milligrams of equivalent B(*a*)P) and heavy metals (in milligrams of equivalent Pb)

Type	Cements	Regional	Local	
		Ozone formation	Carcinogens	Heavy metals
I	Cement Portland I	14.90	0.000021	0.0058
	Cement CH	–	0.0011	4.01
	Cement N	53.50	0.00034	0.53
	Portlandcement NL1	1.19	–	–
	Cement S	53.50	0.00034	0.53
	Cement SF1	367.00	0.0046	0.11
	Cement SF2	6.33	0.0014	0.38
II	Cement Portland	174.00	–	–
	Portlandcement A	95.50	0.00015	0.12
	Portlandcement NL2	–	–	0.013
	Portlandcement NL3	8.68	–	–
III	Cement Hoogoven I	12.70	0.000022	0.0059
	Cement blast furnace slag	363.00	–	–
	Blastfurnace slag cement NL1	–	–	0.013
	Blastfurnace slag cement NL2	3.74	–	–
IV	Cement Portlandash	182.00	–	–

7. Conclusions

The characterisation of the environmental impact of manufacturing 1 kg of a variety of cements, undertaken according to the LCA methodology, has led to the following conclusions:

- The errors and ambiguities of system boundaries as described in Ref. [6] have again been observed. This is logical, as characterisation is a phase that takes place after an inventory is made, and which works from the environmental interventions it states. Consequently, inventories should be defined consistently, and their system boundaries must be adequately defined, structured and described to be able to get reliable results. These errors and ambiguities can be relevant in cradle to grave analysis of specific applications, though the final effect will mainly depend on the importance of cement in the whole life cycle analysed (higher, for instance, in isolated concrete structures and lower in more complex functional units like complete buildings where maintenance can be particularly important).
- Carbon dioxide (CO_2) is the main cause of the greenhouse effect and ranges between 98.8% and 100% of the total. The influences of other gases (methane, CH_4 or nitrous oxide, N_2O), despite their higher characterisation factors, are much smaller. Quantitatively, CO_2 emissions are significant and range in the order of 800 g of CO_2 in the production of 1 kg of Type I cement.
- Acidification is mainly caused by SO_2 and NO_x emissions. The total acidification (in g of equivalent SO_2) depends on the type of cement (its content in clinker). These values range from 1.1 to 3.4, with an average of 2.2 (Type I), 1.2 to 3.3, with an average of 2.0 (Type II) and 0.6 to 2.5, with an average of 1.2 (Types III and IV). NO_x emissions are the prime source of acidification, while the effect of HCl and NH_3 is practically negligible. The values obtained are in line with typical emissions of cement plants and with emission limits, despite including more stages in the life cycle (cradle to gate).
- The main cause of eutrophication is the emission of NO_x. The remainder of the emissions has a negligible effect on this environmental impact. The results for Type I was 125–480 mg of equivalent PO_4, with an average of 300, whereas for Type II

the values were 90–400, with an average of 270, and for Type III, 50–140, with an average of 90. These results mean that a cement plant that produces 1 million tonnes a year also produces a phosphorus load of approximately 0.5 kg per hectare (assuming an influence distance of about 35 km – 20 miles – surrounding the cement plant), which is in line with typical phosphorus loads for industrial areas of Western Europe.

- For winter smog (small dust particles in suspension in the air), the main sources are SO_2, dust and soot. The results show that emissions of soot have a negligible effect and that there is a great disparity in the inventoried influences of SO_2 and, very particularly, of dust. From the analysis conducted and taking into account the emission limits of the countries from which the cement inventories come, it is highly likely that this disparity comes from the mining and preparation of energy resources in the countries of origin.
- In the cases of photochemical ozone formation (summer smog), heavy metals and carcinogens, the results are highly variable and depend on the fuels and raw materials used. In most cases, emissions stem predominately from energy-producing processes and in particular the production of electricity and the refining of primary fuels (crude oil, coal, etc.). Thus, despite the environmental loads that are implied within the boundaries of the system of cement production, the processes correspond to zones that are likely not to be local to the cement plants themselves.

Acknowledgements

The authors wish to acknowledge the aid they received through a number of projects funded by public (CICYT, Interministerial Science and Technology Commission) and private (IECA, Ciment Català) bodies.

References

[1] International Organisation for Standardisation, ISO 14040, Environmental management, Life Cycle Assessment, Principles and framework, Geneva, 1997.
[2] Cement and Concrete Association of Australia, The Sydney House, Life Cycle Assessment, Report, 2001.
[3] International Organisation for Standardisation, ISO 14041, Environmental management, Life Cycle Assessment, Goal and Scope Definition and Inventory Analysis, Geneva, 1998.
[4] The Nordic Council of Ministers, Product Life Cycle Assessment, Principles and Methodology, Nord, Copenhagen, 1992:9.
[5] Wrisberg, N. (coordinator), Definition Document, LCANET Board, Leiden, 1996.
[6] A. Josa, A. Aguado, A. Heino, E. Byars, A. Cardim, Comparative analysis of available life cycle inventories of cement in the EU, Cem. Concr. Res. 34 (8) (2004) 1313–1320.
[7] Pré Consultants bv, SimaPro software, v. 4.0, Amesfoort, 1997.
[8] Intron, An Overview of Available LCI Data: Cement, Concrete and other Building Materials, Intron report No. 97079, Sittard, 1997.
[9] Swiss Federal Institute of Technology, Environmental Life-Cycle Inventories of Energy Systems, An Environmental Database for the Accounting of Energy Inputs in Product Life Cycle Assessment and the Comparative Assessment of Energy Systems, Institute of Energy Technology, Zurich, July 1994.
[10] H. Lundström, G. Ölund, T. Rydberg, Life cycle assessment of a concrete sewage pipe, CIT ecologic, Chalm. Indust. (1996).
[11] F. Hoefnagels, V. de Lange, De milieubelasting van houten en betonnen dwarsliggers, Consultancy and Research for Environmental Management, Amsterdam, February 1993.
[12] Chalmers University of Technology, LCA of Building Frame Structures, Environmental Impact Over the Life Cycle of Concrete and Steel Frames, October 1996.
[13] T. Häkkinen, K. Mäkelä, Environmental adaption of concrete, Environmental Impact of Concrete and Asphalt Pavements, Technical Research Centre of Finland, Espoo, 1996.
[14] M. Vold, A. Ronning, LCA of Cement and Concrete, Stiftelsen Østfoldforskning, Fredrikstad, November 1995.
[15] H.M. Knoflacher, P. Tuschi, A. Medwedeff, Die ökologische Standortbestimmung des in österreichischen werken hergestellten Bindemittels zement, Vienna, June 1995.
[16] A. Schuurmans, Milieumatenconcept voor de bouw deterministische uitwerking proefproject weg, Intron-report, vol. 93278, November 1994.
[17] P. Fraanje, H. Jannink, V. de Lange, R. Lim, Milieubelasting van twee aanbruggen - pilot study, Interfacultaire Vakgroep Milieukunde Universiteit van Amsterdam, Amsterdam, May 1992.
[18] R. Heijungs, J.B. Guinée, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleewijk, A.M.M. Ansems, P.G. Engels, R. van Duin, H.P. de Goede, Environmental Life Cycle Assessment of Products — Guide and Backgrounds, Centre of Environmental Science, Leiden University (CML), Leiden, The Netherlands, 1992.
[19] M. Goedkoop, R. Spriensma, The Eco-indicator 99: a damage oriented method for life cycle assessment, methodology report, second edition, Pré Consultants, Amersfoort, The Netherlands, 2000.
[20] H. Wenzel, M. Hauschild, L. Alting, Environmental Assessment of Products, Methodology, Tools and Case Studies in Product Development, vol. 1, Chapman and Hall, 2000.
[21] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. Wegener Sleeswijk, H.A. Udo de Haes, J.A. de Bruijn, R. van Duin, Life cycle assessment: an operational guide to the ISO standards, volume 1: LCA in perspective, volume 2: Guide, volume 3: Scientific backgrounds, Centre of Environmental Science, Leiden University (CML), Leiden, The Netherlands, 2000.
[22] M. Goedkoop, M. Oele, S. Effting, SimaPro 6 Database Manual — Methods library, v. 2.0, PRé Consultants, Amersfoort, the Netherlands, 2004.
[23] M.A. Curran, Life Cycle Assessment: Principles and Practice, Scientific Applications International Corporation (SAIC), National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 2006.
[24] O. Jolliet, R. Müller-Wenk, J. Bare, A. Brent, M. Goedkoop, R. Heijungs, N. Itsubo, C. Peña, D. Pennington, J. Potting, G. Rebitzer, M. Stewart, H. Udo de Haes, B. Weidema, The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative, Int. J. LCA 9 (6) (2004) 394–404.
[25] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, H. de Bruijn, R. van Duin, M.A.J. Huijbregts, Handbook on Life Cycle Assessment, Operational Guide to the ISO Standards, Kluwer Academic Publishers, Dordrecht, 2002.
[26] M. Hauschild, H. Wenzel, Environmental Assessment of Products, Scientific Background, vol. 2, Chapman and Hall, London, 1998.
[27] J.C. Bare, G.A. Norris, D.W. Pennington, T. McKone, TRACI: the tool for the reduction and assessment of other environmental impacts, J. Ind. Ecol. 6 (3–4) (2003) 49–78.
[28] B. Steen, A Systematic Approach to Environmental Priority Strategies in Product Development (EPS), v. 2000, a) General System Characteristics, b) Models and Data, Chalmers University of Technology, Centre for Environmental Assessment of Products and Material Systems (CPM), Report 1999:4 and 5, Gothenburg, 1999.
[29] J.T. Houghton, L.G. Meira Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, B.A. Callander, Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories — Reporting instructions, volume 1, IPCC/OECD/IEA, Intergovernmental Panel on Climate Change, UK Meteorological Office, Bracknell, UK.

[30] Cembureau, World Cement Directory, Brussels, 2002.
[31] A. Josa, A. Aguado, R. Gettu, Life Cycle Assessment of Concrete Products, Proc. 5th National Congress on Concrete — Durability, Cemal Resit Rey Konser Salonu, Harbiye, Ed. Maya basin Yayin, Estambul, pp. 279–292.
[32] A. Josa, R. Gettu, A. Aguado, Environmental Evaluation of Cement-Based Products, in: I+D+i en tecnología de estructuras de hormigón — R+D+i in technology of concrete structures, Ed. Departament d'Enginyeria de la Construcció de la U.P.C., Barcelona, 2004.
[33] European Commission, Integrated Pollution Prevention and Control (IPPC), Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries, Brussels, 2001.
[34] European Parliament and Council, Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the Incineration of Waste, Brussels, 2000.
[35] Oficemen, Acuerdo voluntario para la prevención y el control de la contaminación, Oficemen, the Spanish Cement Association, Madrid, 2001.
[36] European Environment Agency, Environmental Signal 2000, Regular Indicator, Copenhagen, 2000.