Carbon Footprint of Concrete Buildings seen in the Life Cycle Perspective

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Abstract

The Danish cement and concrete industry has worked hard to reduce the environmental footprint of concrete for the past 15 years. The use of supplementary cementitious materials is normal procedure on almost every concrete plant. Especially fly ash is added extensively for all types of concrete applications.

The primary environmental indicator is still the CO_2 footprint when concrete is assessed and compared with other structural designs. However, even though concrete is known to have a relatively high CO_2 emission during production it is of paramount importance to include the service life of buildings in this type of calculations. The thermal mass of concrete helps improve the energy performance of a building which again will reduce the effect of a high initial CO_2 footprint. A slight difference in the energy performance of a building design may tip the balance from an environmentally sound design to the direct opposite in terms of energy performance. After end of service life concrete is suitable for recycling back into construction applications. Furthermore, the concrete rubble will carbonate and absorb CO_2 from the atmosphere.

The paper will demonstrate these issues through examples where the benefits of heavy building materials are illustrated. The inherent high thermal mass of concrete is used to improve the energy performance of buildings as well as the thermal comfort compared with light weight materials.

Introduction

Danish Technological Institute has worked with concrete and its role for the environment together with the cement and concrete industry. We are involved in international networks spreading the knowledge on how to produce green concrete structures that are sustainable and how to design green concrete. It is our impression that the focus is shifting from a purely material orientated baseline towards a more broad definition where all life cycle phases are included. It is very important to disseminate proper information on these subjects so that material manufacturers, designers and building owners are able to apply the knowledge with benefit to society. A recent overview of the Danish activities is provided in Nielsen and Glavind (2007).

The global warming and greenhouse effect are highly profiled issues that are becoming more and more visible in the media. It is now part of everyday language to refer to CO_2 emissions coming from daily routines. Therefore, it is chosen to focus on the CO_2 emissions in this article.

Concrete and the environment. Generally concrete is seen as a versatile material being absolutely necessary for a society to develop its infrastructure and housing and in order to prosper. Concrete is mainly based on natural resources readily available in all corners of the globe in huge amounts, i.e. a very local building material. It is generally considered to be a sustainable material due to its good inherent properties such as strength, fire protection, earthquake proof and fully recyclable. However, concrete production is also associated with environmental impacts that make it necessary to adopt certain awareness when producing it and using it in structures:

- Manufacturing of cement is rather energy demanding and each kg of Portland clinker emits almost 1 kg of CO_2 to the atmosphere. Therefore it makes good sense to substitute part of the clinker content with residual materials from other industries (FA, GGBFS, etc.). Substitution levels of say 30 % (by weight of total binder) should be possible for most applications without impairing the strength performance (Malhotra 1999, EcoServe 2006).
- In certain (densely populated) regions natural resources are scarce and therefore, demolition waste (concrete and masonry rubble) should be utilized as substitute for natural materials to the largest extent instead of being land filled (Figure 1 and 2).
- Also water resources are exploited when producing concrete (EcoServe 2006). The concrete manufacturer should recycle washing water for the mixer and trucks in a closed-loop system instead of discharging the highly alkaline water to the sewer system.

These issues have been amongst the main drivers for the cement and concrete industries' efforts to produce greener products in recent years. However, it should be kept in mind that this is a complicated balance, where the concrete industry on one hand is trying to reduce the carbon footprint of concrete by blending the cement and optimizing the mixture design. But on the other hand the contractor has a strong incitement to speed up strength development and casting rates which again speaks for higher cement clinker content. Thus, there is a need for the building owners to specify greener concrete and labeling schemes such as the LEED is one way to obtain this.

Throughout the past 5 years research activities have been carried out as collaboration between the Nordic countries (Pade and Guimaraes 2007) in order to assess the effect of including carbonation and CO_2 uptake from the atmosphere. Seen on a geological time scale all the CO_2 emitted from the calcination process will be reabsorbed during carbonation. Especially after end of service life and after being crushed into concrete rubble the carbonation process speeds up and becomes significant (Fig 1). It is recognized that carbonation is a diffusion process depending on the concrete quality and the exposure conditions to atmospheric air and thus, difficult to predict and slowly by nature. However, it is also recognized that the effect should be included when concrete embodied CO_2 figures are calculated. This is illustrated further in this article.

There is a tendency that whenever an unwanted residual material is located (old tire rubber, crushed glass, various ash materials from incineration processes and so forth) it may simply be granulated and cast into concrete as a filler material. These solutions may be possible locally in regions where such residual materials are sufficient in quantity to support a production plant but it is never going to be the general picture because the amounts are not large enough to support a stable homogeneous material flow. Care should also be taken in order not to mix dangerous substances into concrete, for instance materials containing heavy metals that may leak into the ground water. By doing this we simply export the problem to our grand children, which is not a sustainable solution.

Figure 1. Mobile crusher sorting concrete rubble into fractions to be used for road construction and back-filling purposes.

Figure 2. Construction and demolition waste may need extensive and costly sorting before it is ready for secondary use.

The construction industry also includes other environmental issues that may be important under certain circumstances. For instance in Denmark the competition for skilled labor and the general wish for higher productivity have promoted the use of self-consolidating concrete significantly (Nielsen 2007). About one third of the ready mixed concrete being produced in Denmark today is self-consolidating. Contractors that switch to SCC find it difficult to go back because his concrete personnel are reluctant to work with conventional concrete again.

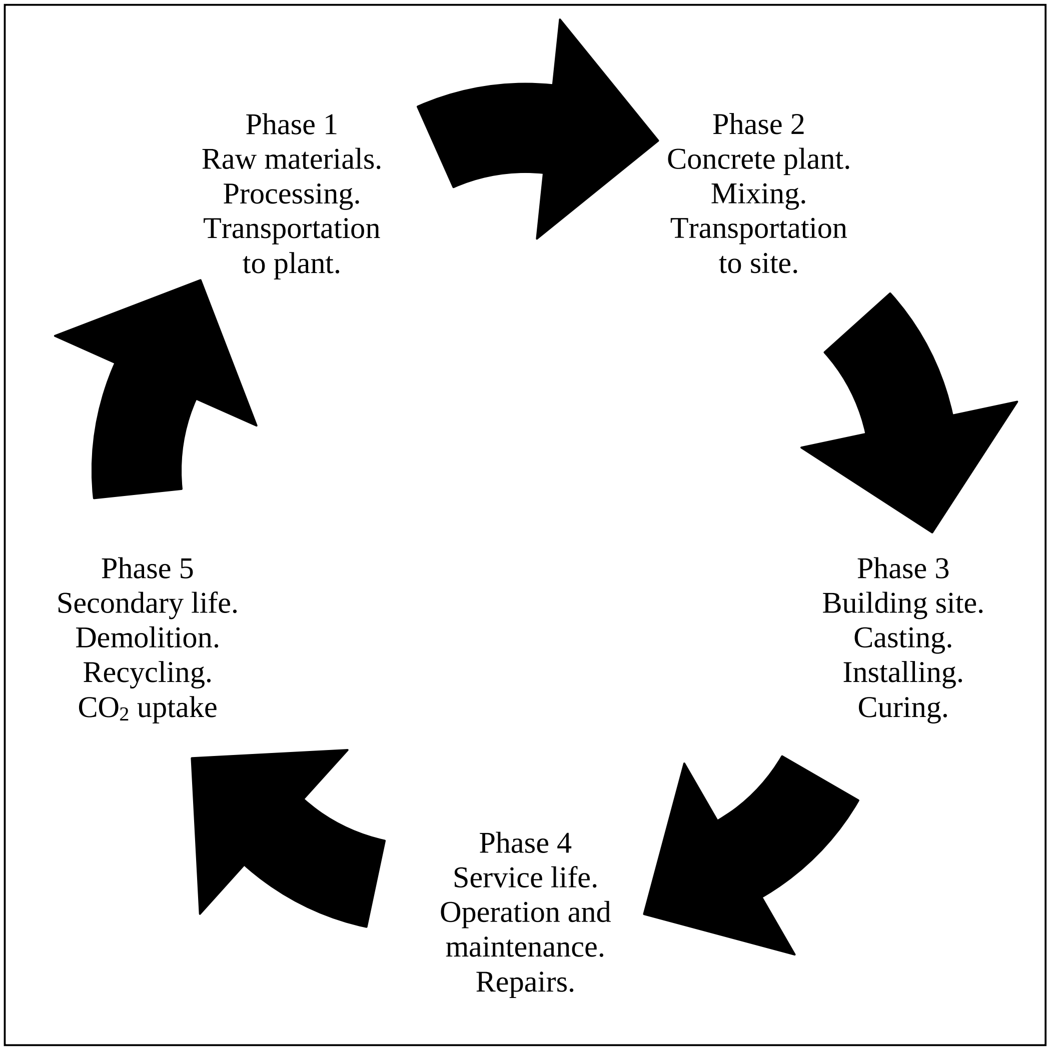

Figure 3. Life cycle phases from cradle to grave. The arrow between phases 5 and 1 illustrates the sorting and recycling of demolition waste back into the construction industry in general and not necessarily back into concrete production.

Scope. In traditional LCA the CO_2 emissions are a part of the total index for a given functional unit alongside other emissions, natural resources, energy use, non-renewable resources, etc. These environmental indicators are all pooled together in an index so that different solutions or designs may be compared directly (Björklund et al. 1996, Adalberth 1999). However, a full LCA is by nature complex and not very transparent and therefore it is suggested to present the environmental profile of a concrete structure simply through its carbon footprint rather than performing a full LCA. The same approach has been taken by Kawai et al. (2005).

Examples of carbon footprint of concrete and concrete structures are given, taking into account the embodied energy during all the life cycle phases (Figure 3). The inventory data are mainly based on European experiences taken from the literature.

Carbon footprint of concrete production, phase 1-3

CO_2 inventory. The literature contains several inventories of the energy consumption and CO_2 emissions related to the production of one unit of concrete (Björklund et al. 1996, IStructE 1999, EcoServe 2004, JSCE 2006). Such inventory data are of course depending on the local conditions at the production site such as climate, energy resources, transportation distances and the general conditions of the equipment and plant facilities. Energy based on fossil fuels emits CO_2 corresponding to approximately 80 g/MJ. Natural gas though, only emits some 55 g/MJ. The production of electricity is accounted for by an emission figure of 132 g/MJ (average for the European Union in 2002, EcoServe 2004).

Transportation of raw materials and final products also generates CO_2 emissions. Figure 4 shows how the transportation of one kg material over one km distance depends strongly on the method of transportation. The variation in emission figures depends on the size of the transportation vehicle and its energy efficiency. A lorry for large transportation (e.g. a concrete truck) will emit around $100 \cdot 10^{-6}$/km while a small lorry for local transportation purposes emits at least twice as much. The figures found in the literature differ quite significantly. Thus, the calculations of the transportation contribution to the carbon footprint must be considered a significant source of scatter to the data and they should be treated carefully. This is especially the case when transportation turns out to be an important contribution for a certain building product.

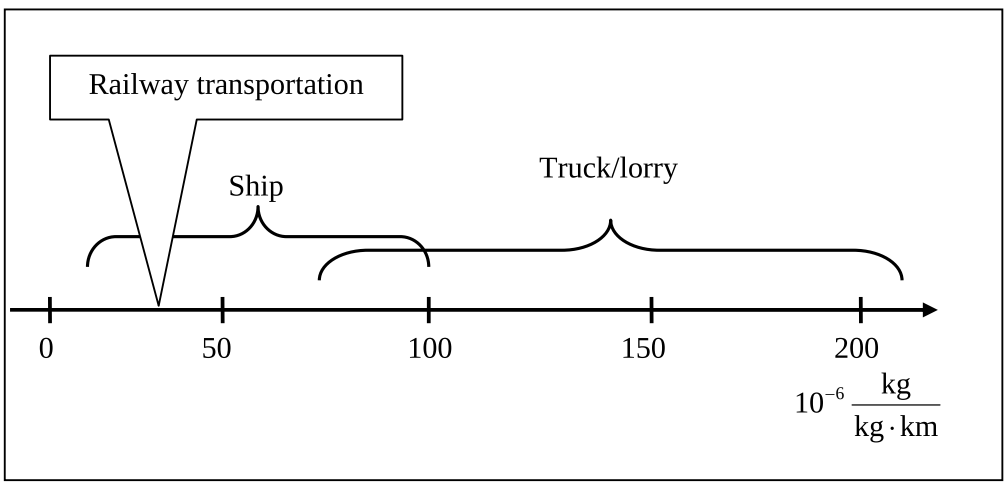

Figure 4. Transportation related CO_2 emissions including empty returns. Collected from Björklund et al. (1996), EcoServe (2004) and JSCE (2006).

Table 1 gives a calculation of the embodied CO_2 amount of one unit volume of ready mixed concrete delivered to a building site and cast into a lightly reinforced structural element. The concrete in Table 1 is strength class 35 MPa (5000 psi) with *w/cm* = 0.4. Figure 5 illustrates the distribution from Table 1 subdivided into phases 1-3 and for the most important CO_2 contributors. It is obvious that cement manufacturing accounts for the major part of ECO2, where ECO2 denotes embodied CO_2 in the following.

The range of the CO_2 emission factor for cement in Table 1 indicate the variation often encountered from various production plants and cement types (Kawai et al. 2005, Josa et al. 2004). The contribution coming from the calcination process taking place in the cement kiln is approximately 0.55 kg CO_2 per kg cement clinker. The cement manufacturing process accounts for say 60 % and the production accounts for another 30 % while the remaining 10 % is transportation and the other constituents (Figure 5). These contribution figures really show the importance of optimizing the amount of cement clinker for the concrete application. Reducing the clinker content by substitution with supplementary cementitious materials such as fly ash really has a dramatic impact on the carbon footprint of the concrete.

Of course the steel reinforcement would contribute stronger if the structure was heavily reinforced with say 100 kg/m^3 (170 lb/yd^3) instead of only 30 kg/m^3 (50 lb/yd^3). The aggregates traditionally accounts for a very small amount of ECO2 even though it constitutes more than 2/3 of the concrete volume. Japanese experiences show that the crushing and sorting of demolition waste has about the same ECO2 as natural materials excavated in quarries. However, there exist certain crushing methods where heat is added to the process to obtain better quality aggregates but then the CO_2 emission increases from about 0.003 to 0.018 kg/kg (Kawai et al. 2005).

Table 1. Embodied carbon balance for production of ready mixed concrete based on Danish figures. Phases 1-3, cradle to building site.
Total embodied CO_2: ECO2 = 402 kg/m^3 = 0.17 kg/kg based on a density of 2400 kg/m^3 (4046 lb/yd^3).

Functional unit: FU = one m^3 (0.765 yd^3)	Production			Transportation		
	A	B ECO2	A·B ECO2	D	E ECO2	A·D·E ECO2
Item	$\frac{kg}{FU}$ (lb/yd^3)	-	$\frac{kg}{FU}$	km	$\frac{kg}{kg \cdot km}$	$\frac{kg}{FU}$
Cement OPC	300 (506)	0.8-0.9	255	100	$100 \cdot 10^{-6}$	3
SCM	29 (49)	0	0	100	$100 \cdot 10^{-6}$	~0
Sand	660 (1113)	0.003	2.0	20	$100 \cdot 10^{-6}$	1.3
Coarse	1170 (1976)	0.003	3.5	20	$100 \cdot 10^{-6}$	2.3
Water	145 (244)	-	-	-	-	-
Steel	30 (51)	1.0	30	500	$100 \cdot 10^{-6}$	1.5
Concrete	2400 (4046)	0,04	96	30	$100 \cdot 10^{-6}$	7.2
		Sum =	**387**		**Sum =**	**15**
-	**-**			**-**	**Total =**	**402**

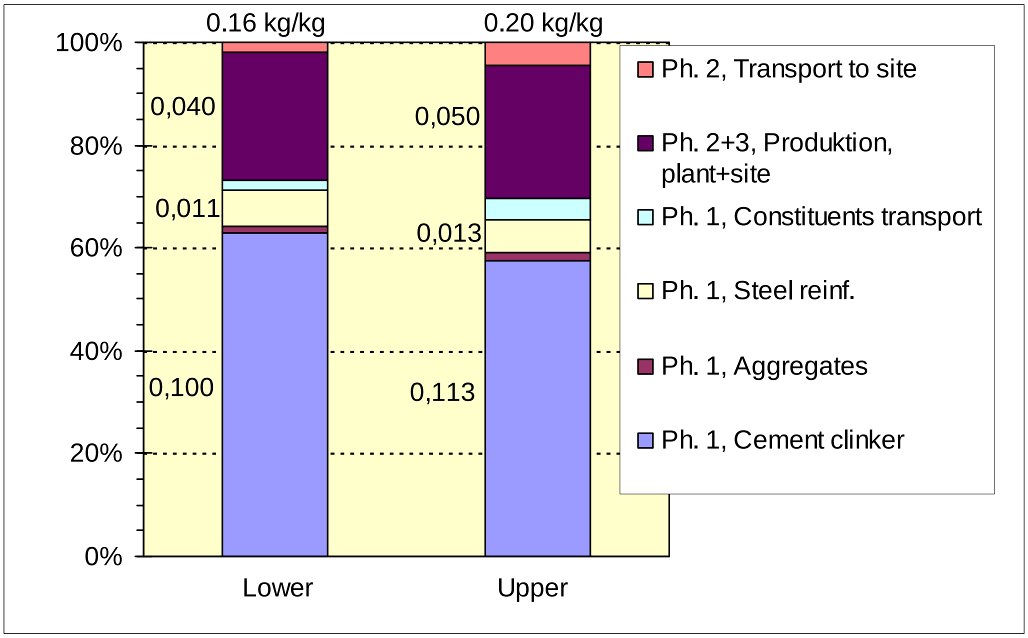

Figure 5. Distribution of ECO2 on the various constituents and phases of the concrete production according to Table 1. Left column is lower values and right column upper values. The figures on the columns depict the ECO2 in kg/kg for the most important contributions. The figure on top of each column is the total ECO2.

The two columns of Figure 5 show the variation to be expected for this type of calculations. The lower value is obtained for short transportation distances and lower emission factors, while the higher value includes longer transportation of constituents and slightly higher emission factors. The transportation distances used in the example are typical for Danish conditions and they should be re-assessed in each case. However, since transportation does not contribute significantly in Figure 5 the accuracy of these data are not crucial for the result.

The range of ECO2 typically will lie from 0.12 kg/kg for plain and lightly reinforced concrete with lower grades up to around 0.20 kg/kg for higher grades and precast structural elements (Björklund et al. 1996, Kawai et al. 2005). Punkki et al. (2007) report values for precast structural elements based on Finnish environmental product declarations ranging from 0.14 to 0.25 kg/kg. The former being hollow core slabs and the latter sandwich wall elements. Similarly Danish findings suggest an ECO2 value of 0.18 kg/kg for precast light weight concrete based on exclay LWA. Light weight concrete is often used as structural wall elements in smaller buildings.

Application in structures. In case of building structures concrete is often an important part together with other building materials such as timber, plaster boards, steel, glass, insulation, masonry, roof tiles, metals, etc. In order to compare the ECO2 of a functional structural unit - say a wall or a slab design - we need to know the inventory data for these materials as well. Again the literature may serve as input. Table 2 shows such a comparison for external wall structures. The structure of Table 2 is similar to that of Table 1. The wall structures comprise:

- A massive wall structure with outer brick leaf and a cavity filled with mineral wool for insulation. Weight of structure is approximately 400 kg/m^2 (82 lb/ft^2).

Table 2. ECO2 for external wall structure. Based on Björklund et al. (1996) and Punkki et al. (2007).

Functional unit FU = one m^2 wall (10.76 ft^2)	Production			Transportation		
	A	B ECO2	A·B ECO2	D	E ECO2	A·D·E ECO2
Item	$\frac{kg}{FU}$	$\frac{kg}{kg}$	$\frac{kg}{FU}$	km	$\frac{kg}{kg \cdot km}$	$\frac{kg}{FU}$
Insulated cavity wall with clay brickwork (110 mm) and 150 mm insulation and pre-cast light weight concrete element (100 mm thickness)						
Masonry bricks	130	0.25	33	100	$100 \cdot 10^{-6}$	1
Mortar	85	0.13	11	20	$150 \cdot 10^{-6}$	~0
Mineral wool	5	1.0	5	100	$100 \cdot 10^{-6}$	~0
LWC element	185	0.18	33	-	-	-
	~400	**Sum =**	**82**	-	**Sum =**	**~2**
					Total =	**84**
Reinforced mortar (30 mm) plastered on 150 mm insulation and precast light weight concrete element (100 mm thickness)						
Mortar plaster	54	0.09	5	20	$150 \cdot 10^{-6}$	~0
Wire reinf.	1	0.8	1	500	$100 \cdot 10^{-6}$	~0
Mineral wool	15	1.0	15	100	$100 \cdot 10^{-6}$	~0
LWC element	185	0.18	33	-	-	-
	~250	**Sum =**	**54**	-	**Sum =**	**0**
					Total =	**53**
Clay brickwork (110 mm), 30 mm air gap and two layers of plasterboards on steel studs (150 mm) with insulation						
Masonry bricks	130	0.25	33	100	$100 \cdot 10^{-6}$	1
Mortar	85	0.13	11	20	$150 \cdot 10^{-6}$	~0
Mineral wool, 150 mm	5	1.0	5	100	$100 \cdot 10^{-6}$	~0
Steel studs	4	0.7	3	500	$100 \cdot 10^{-6}$	~0
Plaster boards	17	0.3	5	50	$100 \cdot 10^{-6}$	1
	~240	**Sum =**	**57**		**Sum =**	**~2**
					Total =	**59**
Reinforced mortar (30 mm) plastered on 150 mm insulation on structural steel frame. Internal stud wall with two layers of plasterboards and insulation (120 mm thickness)						
Mortar plaster	54	0.09	5	20	$150 \cdot 10^{-6}$	~0
Wire reinf.	1	0.8	1	500	$100 \cdot 10^{-6}$	~0
Mineral wool, 150 mm	15	1.0	15	100	$100 \cdot 10^{-6}$	~0
Steel studs	4	0.7	3	500	$100 \cdot 10^{-6}$	~0
Steel frame	30	1.0	30	500	$100 \cdot 10^{-6}$	2
Mineral wool, 100 mm	3	1.0	3	100	$100 \cdot 10^{-6}$	~0
Plaster boards	17	0.3	5	50	$100 \cdot 10^{-6}$	1
	~140	**Sum =**	**62**	-	**Sum =**	**3**
					Total =	**65**

- A combination where the outer brick leaf is substituted with mortar plaster directly on the insulation. This reduces the weight of the structure significantly to approximately 250 kg/m^2 (51 lb/ft^2)..
- Another semi light weight structure with brick outer leaf and mineral wool between the steel studs of a plaster board internal wall. Total weight is approximately 240 kg/m^2 (49 lb/ft^2).
- The most light weight structure in this comparison is reinforced plaster on insulation attached to a steel frame. The inner wall finish is a stud wall with plaster boards. Total weight of structure is approximately 140 kg/m^2 (29 lb/ft^2).

It is clear that the heavy wall structure, based on concrete and bricks, has a higher ECO2 than the lighter building frames. Note that clay bricks and concrete show almost identical carbon footprint per unit area. The difference between the highest and the lowest ECO2 is about 30 kg CO_2 per m^2 wall (6 lb/ft^2). It is obvious from the calculations that the transportation of building materials to the building site is of minor importance unless the transportation distances are extreme. Note also that even though the wall designs have similar energy performance they are not necessarily identical when it comes to durability and maintenance.

However, as it is demonstrated in the following the different material choices will influence the energy consumption during the service life of the building. It can also be argued whether a massive structure has other benefits in terms of fire resistance, noise protection and less maintenance than a light weight solution. All of these issues should be dealt with during the design phase and they are not included in the present comparison.

For a whole building the difference in ECO2 may be calculated per unit floor area by adding all the building structures (roof, walls, floor slabs, etc.) and dividing by the total floor area. Each structural element may be calculated according to the scheme in Table 2. Hacker et al. (2006) contains such an inventory for a semi-detached house of totally 66 m^2 floor area (710 ft^2), being a typical starter home for a family in the UK. The calculations of ECO2 show the following figures per unit floor area:

- Common elements (concrete slab on grade, outer brick leaf, roof structure, installations, carpets, doors, windows, etc.) amount to ECO2 = 424 kg/m^2.
- The light weight structures (plaster board walls and timber structure) add the following amount to the common elements: ECO2 = 59 kg/m^2.
- The heavy weight frame, consisting of light weight concrete and hollow core slab partition, adds the following amount to the common elements: ECO2 = 104 kg/m^2.

Thus, the difference in ECO2 amounts to 45 kg CO2/m^2 in the UK investigation (Hacker et al. 2006). Calculation of such differences in embodied CO_2 emissions between different building materials and building frame designs is of course followed with a rather high variation due to the accuracy of the calculations and the quality of the input data. It is estimated that the ECO2 differences per unit floor area are normally ranging from 30 to 70 kg CO_2/m^2, depending on the size, the type and the location of the building. This interval is used in the following section to evaluate the total life cycle CO_2 emissions for a building.

Carbon footprint from operation of buildings, phase 4

The operation of buildings during their service life is the main contributor to the CO_2 balance over its full life cycle. Heating and ventilation and cooling of buildings are responsible for about 80 % of the total energy consumption including the embodied energy corresponding with the production of the building (Adalberth 1999). Since the service life is often 50-70 years or even more the annual energy consumption has very large impact on the total carbon footprint of a building. For this reason alone it makes good sense to design the building with minimum energy consumption in mind. European figures show that more than 40 % of primary energy is used for operation of buildings (ECP 2007). Furthermore, over half of the operation energy is used for heating of building space (ECP 2007). The authorities regulate the criteria to the building energy performance mainly through specifications on the maximum heat loss coefficient for floors, walls, windows, etc. The designers have to meet these specifications in the design phase before the building is constructed in order to obtain a building permit. Hence, it is of paramount importance that the designers have the proper calculation tools and knowledge in order to design the building in an environmentally friendly and sustainable way.

Thermal mass effect. Concrete and other heavy materials have a series of positive impacts on the energy consumption of buildings due to its high thermal mass (Hacker et al. 2006, Biasioli and Öberg 2007, ECP 2007). The thermal mass of such materials is influencing the daily temperature fluctuations within the building so that the indoor temperature is better kept within the thermal comfort zone (Figure 6). During summer conditions concrete stores the heat during mid day releasing it in the night time. The heat is partly solar radiation throught the windows but also the free heat gains from persons, electrical equipment and so forth. Thus, high thermal mass reduces the need for cooling. This is especially a benefit to office buildings where working efficiency is influenced by the temperature level during the day time. During winter conditions a high thermal mass may be utilized to store heat from floor heating systems releasing it slowly and homogeneously over a period of time.

The effect is mainly governed by the materials in contact with the indoor air. Therefore, the outside material design of the building envelope is not the most important aspect to consider. It is a necessity that the material and the air are in direct contact and therefore lowered ceilings, furniture along the walls and carpets and flooring on top of concrete slabs have great impact on the thermal mass effect which again makes it a complex matter to include in this type of calculations.

Biasioli and Öberg (2007) perform energy balance calculations for a residential building and an office building located in different climates from northern Scandinavia to southern Europe. The building frame is either heavy (based on concrete frame) or light weight (based on plaster boards stud walls). The calculations are performed by means of different commercially available computer programs and the heavy building frame shows reduced energy consumption compared with the light weight building in all cases. For northern Europe the annual difference in energy for heating/cooling/ventilation between a heavy and a light weight building is ranging from say 10 MJ to 20 MJ per m^2 of heated floor area (Biasioli and Öberg 2007, Punkki et al. 2007). Applying an average emission figure from the EU of 132 g CO_2 per MJ energy (electricity according to EcoServe 2004) we obtain an annual difference of 1.3 to 2.6 kg CO_2/m^2 in favour of the heavy building frame. Punkki et al. (2007) also demonstrate how active heating systems built into the concrete slabs and walls may enhance this difference when concrete is used as a heat storage medium being able to activate even massive concrete structures instead of just the surface layers of concrete.

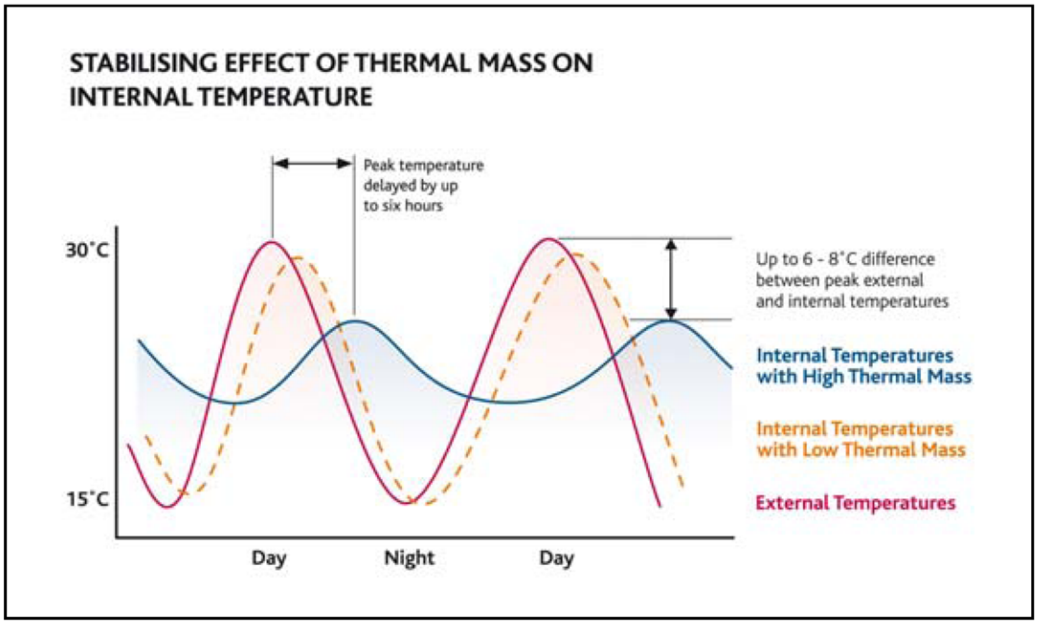

Figure 6. Effect of high thermal mass on the daily temperature fluctuations. Taken from the UK Concrete Centre brochure "Thermal Mass in Housing" (ECP 2007).

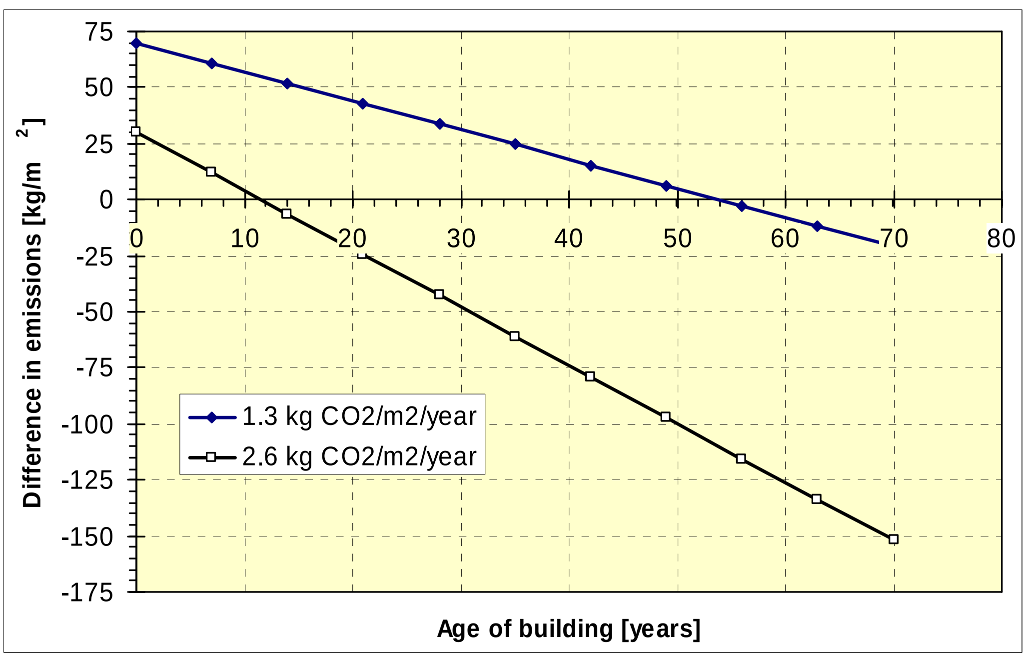

Figure 7. Difference in carbon footprint between light weight building with low thermal mass and a heavy building having high thermal mass. The two lines indicate the range of variation for this type of calculations.

Total carbon footprint. Figure 7 is adding up the initial carbon emissions treated in the previous section and the emissions during the building's service life. Note that Figure 7 is depicting the differences between the two building designs and not absolute emission figures. Initially the footprint of the heavy building frame is higher than the light weight solution as it is demonstrated in the previous section. The difference ranges from 30 to 70 kg/m^2. However, since the energy consumption during operation of the concrete building is lower due to its higher thermal mass this initial difference is slowly reversed and after a number of years the heavy building frame ends up showing the lowest carbon footprint (negative difference). It can be argued that a light weight building frame requires more maintenance than a heavy building frame (Hacker et al. 2006) and therefore the difference will grow even faster than indicated in Figure 7 but this is not included in the present calculation.

The pay-back time is taken as the period until the difference reverses from positive to negative figures. Depending on the conditions pay-back times ranging from 10 to 50 years are possible, being in agreement with the findings of Punkki et al. (2007).

Carbon footprint after end of service life, phase 5

The calculations in Figure 7 stop at 70 years service life but often buildings are in operation even longer than that and in that case the difference will continue to develop. However, in many cases 70 years service life will mean a major refurbishment depending on the general condition of the building, on its function and on its ability to meet the energy performance demands from the authorities. This is very much an individual decision taken for each building by its owner.

After end of service life the building is demolished, under energy consumption and CO_2 emissions. JSCE (2006) estimates the demolition process to be accounted for by an emission of 0.004 to 0.01 kg CO_2 per kg concrete material, depending on reinforcement, the type of structure and the working conditions in general on the demolition site. For light weight materials the emission figures are much lower and often negligible. After proper sorting and reclamation of steel reinforcement the demolition waste is then crushed down to different fractions in order to be recycled back into construction again (Figure 1 and 2). The crushing process costs emissions around 0.001 to 0.003 kg/kg (JSCE 2006), i.e. totally 0.005 to 0.013 kg/kg for the whole of phase 5.

Now we take a look on the amount of CO_2 originally released during the cement manufacturing (Figure 4), being around 0.05 kg/kg. The carbonation process will be able to reabsorb around 60 % of the original CO_2 emission from the cement production (Pade and Guimaraes 2006). The process is taking place rather slowly during the service life of the structure but after crushing it is speeded up significantly due to the highly increased specific surface area being exposed to atmospheric air in the rubble piles (Figure 1). If we assume a potential efficiency of 50 % on this CO_2 uptake process we obtain 0.6*(0.05 kg/kg)*0.5 = 0.015 kg CO_2 being reabsorbed per kg concrete demolished and crushed. Comparing the CO_2 uptake with the emissions related to the demolition and crushing process it is seen that they practically balance each other out making the recycling of concrete demolition waste CO_2 neutral. It is recognized that is a very rough calculation that need further detailing in order to be generally applicable but here it is just meant to demonstrate the order of magnitudes and to put the demolition phase into the life cycle perspective.

Conclusions

A general methodology for CO_2 emission calculations has been given. Examples of such calculations are presented based on inventory data from the literature. Furthermore, the need for including the full life cycle is demonstrated. It has also been demonstrated how the accuracy of life cycle inventory data may influence the outcome of such calculations. The following general conclusions are drawn from the calculations:

- Concrete is a building material that will increase the carbon footprint in terms of embodied CO_2 during the production phases, compared with light weight material solutions.
- The main contributor to the concrete carbon footprint is the cement manufacturing process and application of supplementary cementitious materials has great potential for emission savings. However, steel reinforcement is also a significant contributor.
- Transportation of raw materials and finished products has only minor influence on the carbon footprint. Only in case of extreme transportation distances it may play a significant role. The inventory data for transportation is very dependent on local conditions on the place of production.
- The high thermal mass of concrete should be utilized to improve the energy performance of buildings. Since the energy consumption for building operation is much higher than the embodied energy in the building materials the service life period is very important to include when different structural designs are compared.
- Heavy building materials with high thermal mass mean less annual energy consumption for heating/cooling/ventilation which again means less carbon emissions. Even a small annual difference will add up to a significant amount over a service life of say 70 years.
- After ended service life concrete should be demolished and crushed down to small fractions suitable for applications in road construction, back-filling material, etc. This reduces the need for land filling and the need for natural aggregates. CO_2 emissions coming from demolishing and crushing of concrete are balanced out by the CO_2 uptake from the carbonation process in the concrete rubble.

The calculations show pay-back times ranging from 10 to 50 years when the difference in carbon footprint between a concrete building structure and a light weight structure is compared. This range includes the variations that lie in this sort of calculations. Due to the data quality of the inventory for different materials and different locations and several other assumptions the accuracy of the results is generally poor. However, as long as the accuracy is reflected in the calculation results the decision makers are able to include it in their evaluations and thereby make sustainable decisions in favor of society.

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Appendix Conversion Factors between US and SI Units

SI unit	equals	US unit
1 kg = 1000 g		2.205 lbs
1 km = 1000 m		0.621 miles
1 kg/m^3		1.686 lbs/yd^3
1 m^2		10.76 ft^2
100 mm		4 in

