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CO_2 Uptake During the Concrete Life Cycle

The CO_2 Balance of Concrete in a Life Cycle Perspective

Prepared by
Knut O. Kjellsen[i], Maria Guimaraes[ii] and Åsa Nilsson[iii]
[i] Norcem A.S, [ii] Aalborg Portland A/S, [iii] Cementa AB
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Author: **Knut O. Kjellsen, Maria Guimaraes and Åsa Nilsson**

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PREFACE

The objective of this project, of which this report is a part, is to provide documentation of concrete carbonation during service life and secondary use. This documentation should be used for environmental assessment of concrete buildings and structures, and to evaluate the effect of concrete carbonation on the overall CO_2 emissions from cement and concrete production in the Nordic countries.

Approximately half of the CO_2 emission from cement production stems from the calcination of limestone, i.e. a process where limestone is burnt and CO_2 gas is released to the atmosphere. Theoretically, hardened concrete binds approximately the same amount of CO_2 in a process called carbonation. The concrete's ability to bind CO_2 and the rate of the process depends on many variables, including the type of concrete and its application.

The methodology and the impact that concrete carbonation has in the assessment of CO_2 emissions from concrete has not been fully documented. Specifically, there is a lack of knowledge about the carbonation of demolished and crushed concrete. The existing models for calculating carbonation do not take into account that the concrete is crushed and recycled after use. Consequently, the contribution of the cement and concrete industry to net CO_2 emissions is strongly overestimated. This overestimation has a significant influence on CO_2 policy; on the criteria for environmental labelling; and on the selection of materials based on principles of environmentally correct design. A comparison of the environmental impacts from different building materials (e.g. concrete versus wood and steel) is at present unfair because of the lack of documentation of the CO_2 uptake in concrete.

The present report is one of five documents published during the project "CO_2 uptake during the concrete life cycle". Three reports cover the background data and the last two reports include the results of the project.

The background reports are:

- Carbon dioxide uptake during concrete life cycle, state of the art, published by Swedish Cement and Concrete Research Institute - CBI, www.cbi.se, ISBN 91-976070-0-2
- Information on the use of concrete in Denmark, Sweden, Norway and Iceland, published by Icelandic Building Research Institute, www.ibri.is, ISBN 9979-9174-7-4
- Carbon dioxide uptake in demolished and crushed concrete, published by Norwegian Building Research Institute, www.byggforsk.no, ISBN 82-536-0900-0

The reports with results are:

- Guidelines – Uptake of carbon dioxide in the life cycle inventory of concrete, published by Danish Technological Institute, www.teknologisk.dk, ISBN 87-7756-757-9
- The CO_2 balance of concrete in a life cycle perspective, published by Danish Technological Institute, www.teknologisk.dk, ISBN 87-7756-758-7

The participants in the project are:

Danish Technological Institute (Project Manager)
Aalborg Portland A/S (head of Steering Committee)
Norwegian Building Research Institute
Norcem A.S
Elkem ASA Materials
Cementa AB
Swedish Cement and Concrete Research Institute
Icelandic Building Research Institute

Financing partners are:

Nordic Innovation Centre
Aalborg Portland A/S
Norcem A.S
Cementa AB

The project was carried out from December 2003 to December 2005.

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1. Abstract

The amount of atmospheric carbon dioxide absorbed in Nordic concrete structures over a 100 year period has been calculated. The CO_2 uptake, or carbonation, occurs gradually and was calculated for an initial service life period of 70 years followed by a 30 year post-demolition period. The processing of demolished concrete to recycled concrete aggregates increase the CO_2 uptake, this was taken into account in the calculation of the total CO_2 uptake.

Over 100 years, one year of Nordic concrete construction is calculated to absorb 0.34, 0.22, 0.24 and 0.021 million metric tons of CO_2 in Denmark, Norway, Sweden and Iceland, respectively. These are quite notable numbers, and imply that about 0.5% of the total national CO_2 emissions will be re-absorbed in concrete in Denmark, Sweden and Norway. The corresponding number for Iceland is about 1%. The calculations show that up to 30% of the total CO_2 emission from cement production, or up to 57% of the CO_2 emission from the so-called calcination process in cement manufacturing, is re-absorbed when the cement is utilized in concrete construction in the Nordic countries.

2. Introduction

Concrete has served society for more than 2000 years, and it is today the most widely applied building material worldwide. Concrete is essential to our modern society as it provides a cost-effective, durable and strong material to nearly all types of infrastructural installations (e.g. bridges, harbours, tunnels, hydropower dams), buildings and houses.

Like most other industrial manufacturing processes, the production of concrete implies emission of CO_2 to the atmosphere. Concrete is a composite material consisting mainly of aggregates, cement and water. The major part of the CO_2 emission from the production of concrete is related to the production of the cement. Production of Portland cement implies calcination of limestone, and the subsequent heating of the calcined limestone to temperatures around 1450°C. In these processes CO_2 is released from limestone (specifically $CaCO_3$) and from the combustion of fuels. The cement industry has put huge effort in reducing the emission of CO_2 over the last decades, and substantial reductions have been achieved.

One important issue seldom considered in the environmental debate of cement based materials is the re-absorption, or uptake, of CO_2 from the atmosphere. Upon exposure to air, concrete will over time absorb atmospheric CO_2. This process is termed carbonation, and is an intrinsic property of Portland cement concrete and mortar. Carbonation will occur during the service life of a concrete structure, and after demolition. Gajda (1) calculated that during the year 2001 the concrete placed in the United States during the past 50 years absorbed at least 69 million metric tons of atmospheric CO_2.

In fact, the absorption of CO_2 in Portland cement based materials (carbonation) can be compared to the absorption of CO_2 in trees (photosynthesis). These processes are shown in Figure 2.1 and they are intrinsic characteristics of cement based materials and wooden materials, respectively. However, while the absorption of CO_2 is accounted for in life cycle analysis of wooden materials such as bio-fuels, it is not yet accounted for in environmental assessments of cement based materials.

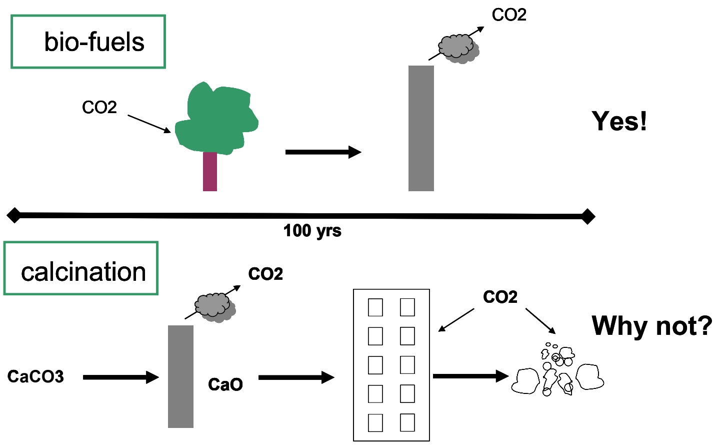


Figure 2.1: CO_2 neutrality in bio-fuels compared, to calcination of limestone in Portland cement production and the subsequent CO_2 uptake in Portland cement concrete.

This report provides documentation of the CO_2 emission from the production of cement and concrete in the Nordic countries, and the extent of CO_2 absorption in concrete structures is calculated. Absorption of CO_2 is considered with respect to the period of service life, and to the phase after the service life (i.e. after demolition).

3. Emission of CO_2 during cement and concrete production

3.1 Concrete production

Concrete is produced by mixing cement with fine aggregate (sand), coarse aggregate (gravel or crushed stone) and water. Small amounts of chemical admixtures are often added to improve workability in the fresh state. When newly mixed, concrete is a plastic material which makes it possible to produce structures of widely different shapes and forms. After a few hours it will stiffen, and upon time it will gradually gain high strength. The setting and hardening result from a chemical reaction between the cement and water (hydration). The properties of concrete in the fresh and the hardened state are determined by the type of cement used, the additives, and the overall proportions (the mix design) of cement, aggregate, and water. The characteristics of concrete; its plasticity in the initial stage and the subsequent development of high strength and high durability makes concrete a unique building material.

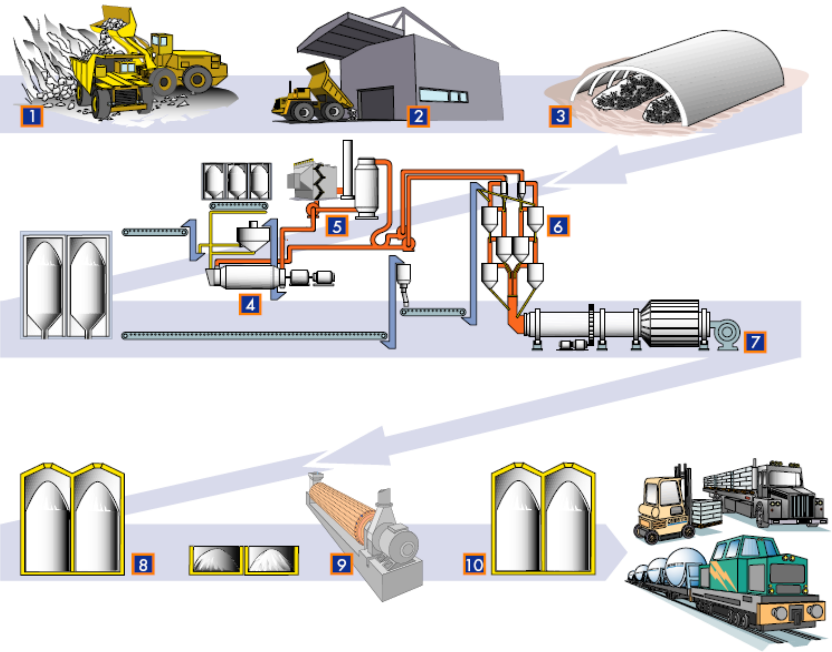
The environmental impact of concrete production comes from various sources, but the main effect comes from the production of cement as exemplified in Table 3.1. Since the major part of CO_2 emission from concrete production originate from cement, and since CO_2 uptake is related to the cement phase, the following section addresses the emissions of CO_2 during cement production.

Table 3.1: Example of CO_2 emission and energy consumption among the ingredients in the production of 1 m^3 ready-mixed concrete (2).

	CO_2 (kg)	Fossil fuel (MJ)	Alternative fuel (MJ)	Electricity (MJ)
Cement	92.3	371.8	117.0	62.4
Aggregate (fine)	2.5	31.7	0.0	1.3
Aggregate (coarse)	2.1	26.5	0.0	8.2
Admixtures	1.5	9.1	1.3	0.4
Water	0.0	0.0	0.0	0.0
Transport	2.5	34.0	0.0	0.0
TOTAL	101.0	473.2	118.3	72.3

3.2 Cement production

Cement has been produced in the Nordic countries for more than 100 years. The development of the cement industry has led to fewer but larger cement production sites. The production process is shown in a simplified form in Figure 3.1. Limestone, which contains mainly calcium carbonate ($CaCO_3$), accounts for about 95% of the raw materials in the production of cement clinker.



1: Quarrying of limestone.
2: Crushing
3: Mixing storage piles
4: Raw mill
5: Filter and silo
6: Cyclone tower
7: Clinker kiln
8: Clinker silos
9: Cement mill
10: Cement silos / unloading

Figure 3.1: A simplified chart of modern production of Portland cement.

The raw materials are heated to temperatures below 1000ºC in the cyclone, which causes calcination of the limestone, according to the following equation (eq. 1):

$$CaCO_3 \text{ (solid)} \Rightarrow CaO \text{ (solid)} + CO_2 \text{ (gas)} \qquad (1)$$

The CaO from the calcined limestone and the oxides from the other raw materials enter the clinker kiln, which consists of a long (60-80 meters) rotating steel pipe. The material is conveyed slowly down to the burner zone of the kiln and is converted to clinker. The gas temperature in the burner zone is about 2.000ºC and the material reaches a temperature of 1.450°C. Portland cement is subsequently produced by inter-grinding clinker with small amounts of gypsum. Emission of CO_2 from cement production originates primarily from the calcination process and from the combustion of fuels in the kiln. The clinker contains about 65% CaO, of which the major part originates from $CaCO_3$. Assuming that all CaO originates from $CaCO_3$, the production of 1 metric ton clinker implies the emission of 510 kg CO_2 from calcination. In modern cement production the total CO_2 emission pr metric ton clinker produced is normally 800-900 kg.

The cement industry has over the last decades reduced the environmental impact from cement production very considerably. Cement manufacturing is a relatively energy intensive process. The very high temperatures used in the cement kiln have one great advantage; the potential for destroying hazardous waste materials such as used motor oil, spent solvents, paint residues, cleaning fluids, scrap tires and municipal solid waste. These waste materials can be burned safely as the extremely high temperatures result in a complete combustion with very low pollution emissions as opposed to municipal solid waste incinerators that operate at considerably lower temperatures. Indeed, for some chemicals, thermal destruction in a cement kiln is the safest method of disposal. Waste derived fuels comprise a significant (and growing) part of the energy mix for cement plants. In this way, coal and oil are preserved and the cement industry help society in the destruction of waste materials.

4. Mechanism of CO_2 uptake in concrete

4.1 Mechanism of carbonation

Carbonation is a chemical process where atmospheric CO_2 reacts with CaO in the concrete to form calcium carbonate ($CaCO_3$). This is the reverse reaction of the calcination process of cement making. In other words, while CO_2 is released to the atmosphere through calcination of limestone and combustion of fuels in the manufacturing process (cf. previous section), CO_2 is re-absorbed again during the life cycle of concrete (i.e. carbonation).

The carbonation process is a relatively slow process as atmospheric CO_2 must diffuse into the concrete and dissolve in the concrete pore fluid. The carbonate ion reacts with the calcium compounds in concrete (primarily $Ca(OH)_2$) and form calcium carbonate according to eq. 2. The detailed reaction schemes can be found in (3).

$$Ca^{2+}(aq) + CO_3^{\ 2-}(aq) \Rightarrow CaCO_3 \qquad (solid) \qquad (2)$$

Carbon dioxide and water are present in all natural environments. Thus, carbonation of concrete is a process that always prevails and it is an intrinsic characteristic of Portland cement based materials. Depending on the concrete composition, the type of concrete structure, and the environment the concrete is exposed to concrete will carbonate totally within years, decades or centuries. In a geological time frame cement based materials will turn into marly limestone (3).

4.2 Rate of carbonation

Carbonation is a process occurring from the surface of a concrete structure and inwards, and depends strongly on the diffusion rate of CO_2 into the concrete. Surfaces in direct contact with carbon dioxide and water carbonate rapidly, while the interior of concrete carbonates at a slower rate.

The rate of carbonation is governed by the size and geometry of the porous structure, the degree of water saturation in the pore system, the type of cement/binder, the chemistry of the pore solution, the temperature, and the concentration of CO_2 in the atmosphere. A high degree of water saturation reduces (but does not eliminate) the carbonation rate. Carbonation is a diffusion controlled process, and the carbonation depth can be approximated with a square root of time equation (eq. 3):

$$d_c = k\cdot(t)^{0.5} \qquad (3)$$

d_c - carbonation depth
k - carbonation rate factor
t - time

The depth of carbonation of concrete is in practice normally measured by spraying the concrete with a solution of the pH-indicator phenolphthalein. Carbonated concrete is colourless while un-carbonated concrete turns pink. This is a simple yet reliable method for determining carbonation depths (1). According to Lagerblad (3) approximately 75 % of the original CaO of the cement is carbonated at the pH of phenolphthalein colour change. The CO_2 uptake in carbonated concrete can thus be calculated according to equation 4:

$$CO_2 \text{ uptake} = \ a = 0.75 \times C \times CaO \times \frac{M_{CO2}}{M_{CaO}} (kg/m^3) \qquad (4)$$

C - mass of Portland cement clinker per m^3 concrete
CaO - mass fraction of CaO in the cement clinker, normally 65%
M - molar mass of CO_2 and CaO, respectively

Ultimately, on a very long time scale, all of the CaO will react with CO_2 to form $CaCO_3$, so that all of the CO_2 liberated by calcination during cement manufacture will be reabsorbed (1, 3).

4.3 Factors affecting carbonation

The rate factor (k) in equation 3 depends primarily on the quality of the concrete and the environment to which the concrete is exposed. The diffusivity of CO_2 in concrete is controlled by the porosity of the concrete. The higher the porosity, the higher is the CO_2 diffusivity. Porosity itself is seldom measured. However, the compressive strength is frequently measured for quality control purposes and this property is controlled by the porosity. Therefore, the diffusivity of CO_2 in concrete of different porosities can be represented by its compressive strength class. Table 4.1 shows carbonation rate factors (cf. equation 3) for various strength classes derived by Lagerblad (3).

The exposure conditions influence the carbonation rate factor considerably, as revealed in Table 4.1. If the humidity is very high the pores in the concrete will be largely filled with water, which implies a low diffusivity of CO_2. On the other hand, if the humidity is too low there is not enough water for the carbonation reactions. The optimal RH for carbonation rate will be 60 to 80 %. Sheltered and indoors structures are normally exposed to this range of RH. Additionally, carbonation rates increase with temperature, which implies a higher carbonation rate indoors compared to outdoors in the Nordic countries. The rate factors given in Table 4.1 agree well with that provided by Gajda (1).

Table 4.1: Carbonation rate factors for various concrete qualities and exposure conditions. (3).

	Compressive strength			
	< 15 MPa	15 - 20 MPa	25 - 35 MPa	> 35 MPa
Exposed	5 mm/$\sqrt{year}$	2.5 mm/$\sqrt{year}$	1.5 mm/$\sqrt{year}$	1 mm/$\sqrt{year}$
Sheltered	10 mm/$\sqrt{year}$	6 mm/$\sqrt{year}$	4 mm/$\sqrt{year}$	2.5 mm/$\sqrt{year}$
Indoors	15 mm/$\sqrt{year}$	9 mm/$\sqrt{year}$	6 mm/$\sqrt{year}$	3.5 mm/$\sqrt{year}$
Wet	2 mm/$\sqrt{year}$	1.0 mm/$\sqrt{year}$	0.75mm/$\sqrt{year}$	0.5 mm/$\sqrt{year}$
Buried	3 mm/$\sqrt{year}$	1.5mm/$\sqrt{year}$	1.0 mm/$\sqrt{year}$	0.75mm/$\sqrt{year}$

5. Concrete production in the Nordic countries

A survey of the volume of concrete produced in the Nordic countries in the years 1950 and 2003 was carried out during this project (4). The concrete production was divided into ready-mixed concrete, pre-cast concrete elements, and pre-cast concrete products. Ready-mixed concrete is concrete made in ready-mix plants, and transported in trucks to the construction site where the concrete is being cast. Pre-cast concrete elements are large structural elements (e.g. walls, hollow-core slabs) produced in factories, and later transported and assembled at the construction site. Pre-cast concrete products are smaller units (e.g. roof-tiles, paving blocks, pipes) that are made in factories and later transported to the construction site.

As previously discussed the carbonation rate depends on concrete strength and exposure conditions. Therefore, information regarding the production volume of the various concrete strength classes, the exposure conditions, and the thickness of various structural elements are needed in order to calculate the volume of carbonated concrete. Careful consideration was made to categorize the volume of various concrete qualities into utilization categories or structural units. Average thicknesses of the various structural units were obtained by best judgement and are presented in Table 5.1.

Table 5.1: Utilization categories and average structural thickness of ready-mixed concrete, pre-cast concrete elements, and pre-cast concrete products, respectively (4).

Ready-mixed concrete		Pre-cast elements		Pre-cast products	
Category	Thickness (mm)	Category	Thickness (mm)	Category	Thickness (mm)
Walls	180	Hollow-core slabs	300	Paving	60
Slabs	200	Other slabs	120	Blocks	160
Foundations	240	Roof	120	Elements	120
Civil eng. structures*	400	Walls	220	Pipes and others	60
		Facades	70+150		
		Columns/Beams	300x300		
		Other	150		

* Heavy civil engineering structures, e.g. bridges, dams.

Each utilization category was sub-divided with respect to the exposure conditions given in Table 4.1. Based on careful consideration, the concrete production volumes obtained from concrete production statistics were distributed to the various utilization categories and exposure conditions. Finally, typical concrete mix design and cementitious material content of the various strength class concretes was obtained. The survey is reported in full detail in (4), and the results are used as input data to the calculation of CO_2 uptake in section 6 of the present report.

The past (1950) and present (2003) production of ready-mix concrete, pre-cast concrete elements, and pre-cast concrete products in the Nordic countries are provided in Table 5.2 to Table 5.4, respectively.

Table 5.2: Production volumes of ready-mixed concrete in the Nordic countries in 1950 and 2003 (4).

	1950 (mill m^3)	2003 (mill m^3)
Denmark	0.7	2.2
Iceland	0.05	0.25
Sweden	4.2	3.2
Norway	1.2	2.4

Table 5.3: Production volumes of pre-cast concrete elements in the Nordic countries in 1950 and 2003 (4).

	1950 (mill m^3)	2003 (mill m^3)
Denmark	0	0.4
Iceland	0	0.02
Sweden	0	0.6
Norway	0	0.3

Table 5.4: Binder consumption for pre-cast concrete products in the Nordic countries in 1950 and 2003 (4).

	1950 (1000 tons)	2003 (1000 tons)
Denmark	498	498
Iceland	2	56
Sweden	176	176
Norway	171	193

6. Recycling of concrete in the Nordic countries

The volume of concrete rubble (i.e. demolished concrete) generated in Denmark, Sweden and Norway amounts to approximately 25% of the concrete produced per year (13% in the case of Iceland). Figure 6.1 shows the volume of concrete rubble generated today, and estimated volume by 2010. The percentage of recycled concrete aggregate (RCA) generated yearly varies considerably among the Nordic countries as shown in Figure 6.2. Note that Iceland does not produce RCA and landfills all of their concrete rubble. The fraction of demolished concrete that is processed to RCA is expected to increase in Norway and Sweden in the next ten years (cf. Figure 6.2). The data reported in Figure 6.1 to Figure 6.3 was obtained from (5).

Recycled concrete aggregate (RCA) is processed from concrete rubble. RCA is crushed concrete that has previously been used in construction, and it can replace natural or crushed aggregates in some applications. Demolished concrete for RCA is generally crushed at crushing plants and stockpiled for a period between 2 weeks and 4 months. It is used mainly in road construction, either as part of the sub-base or as a top layer in minor roads. The use of RCA as aggregate in concrete production is very limited, and in some cases not even allowed.

The extent of carbonation of RCA depends on the surface area of the concrete particles. Since RCA is crushed concrete rubble, it has a relatively large surface area and may thereby absorb more CO_2 through carbonation. However, the rate of carbonation also depends on the exposure conditions as previously discussed. The actual exposure conditions of RCA are presented in Figure 6.3. Note that most of the recycled concrete aggregate in Nordic countries is used in below ground application, where the rate of carbonation is lower than in above ground applications.

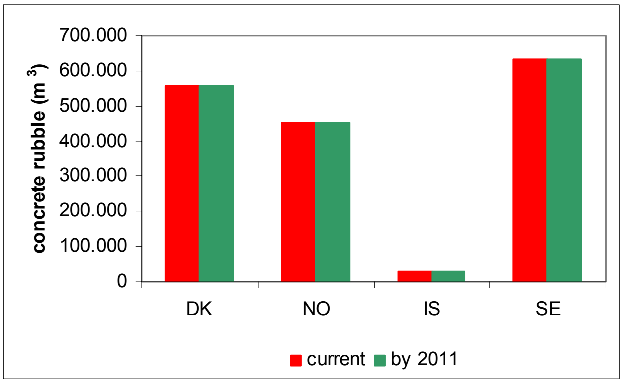


Figure 6.1: Concrete rubble generated annually

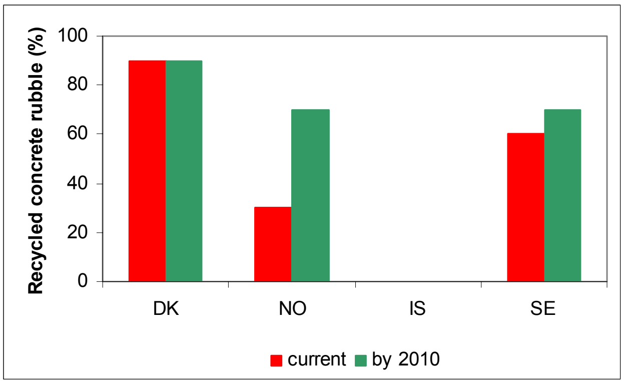


Figure 6.2: Percentage of concrete rubble that is recycled (RCA)

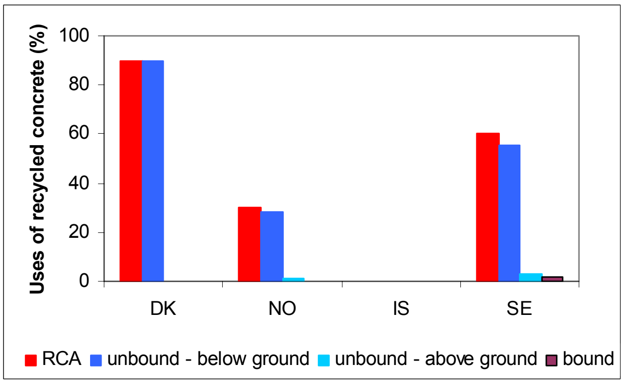


Figure 6.3: Uses of recycled concrete aggregate

7. Uptake of CO_2 during the life cycle of concrete

7.1 Calculation of carbonation for the service life period

The information obtained during this project on concrete production volumes, volumes of recycled concrete aggregates and rates of carbonation have been used to calculate CO_2 uptake of concrete produced in the Nordic countries. Concrete carbonation is calculated for up to 100 years, assuming an average service life of 70 years and a 30 year period after demolition. Each country is treated separately, and calculations are made for concrete produced in 1950 and 2003, respectively.

The calculation of CO_2 uptake is made separately for each concrete utilization category listed in Table 5.1. For each utilization category the total concrete production volumes were obtained (cf. section 5) and a further sub-division into various exposure conditions and concrete strength classes were made (4). The total surface area of each utilization category or structural unit was estimated by dividing the total concrete production volume with the average structural thickness and multiplying with a factor representing the type of structural unit (cf. Table 5.1). This factor should equal the number of sides exposed to carbonation. For example, for walls this factor was set to two assuming that carbonation occurs from both sides of the wall.

The carbonation depth is calculated according to equation 3, with the carbonation rate factors as provided in Table 4.1. The volume of carbonated concrete is then calculated based on the calculated carbonation depth and the total surface area of the structural unit type or utilization category. The amount of CO_2 (kg) absorbed pr m^3 of carbonated concrete is calculated according to equation 4. The total amount of CO_2 uptake is then obtained by multiplying equation 4 with the calculated volume of carbonated concrete.

An example for calculating concrete carbonation during a 70 year service life period is provided in Table 7.1. The example regards 'concrete blocks' produced in Denmark in 2003. The example shows that approximately 50% (76.264 m^3) of the volume of concrete used for blocks in Denmark will be carbonated in the service life period of 70 years.

7.2 Calculation of carbonation after demolition

The calculation of concrete carbonation after demolition assumes that after 70 years in service only the concrete that does not belong to exposure conditions 'buried' or 'wet' will be demolished. When demolished concrete is processed to recycled aggregate (RCA) the surface area of the concrete increases dramatically with a consequent increase in carbonation. The exposed area of RCA is calculated assuming spherical particles and the average particle size distribution of RCA in each country (5). An example of the calculation of concrete carbonation of recycled concrete aggregate (RCA) is provided in Table 7.2. In this example the carbonation after demolishing of all pre-cast concrete products (PCP) produced in Denmark in 2003 is calculated. According to these calculations approximately 75% (502.906 m^3) of pre-cast concrete products that is demolished, and is not already carbonated, will carbonate within 5 years after demolishing.

Table 7.1: Calculation of carbonation during the service life of concrete blocks produced in Denmark in 2003.

Step	Calculation	Example
1	Volume of concrete blocks produced in Denmark in 2003 (4)	153.846 m^3
2	Thickness of structural unit, data from (4)	0.08 m
3	Surface area exposed to CO_2 assuming that all six sides carbonate	(Volume / thickness) x 6 = 11.538.462 m^2
4	Exposure environment (4)	Buried
5	Strength class (4)	35 MPa
6	Carbonation rate for buried concrete from **Fejl! Henvisningskilde ikke fundet.**	0.00075 ($m/yr^{0.5}$)
7	Coefficient to account for the contribution to carbonation of 14% limestone present in CEM II A/L (3)	1.05
8	Modified carbonation rate (eq. 3)	0.00075 x 1.05 = 0.00079 ($m/yr^{0.5}$)
9	Carbonated volume after 70 years = Exposed area (step 3) x carbonation rate (step 8) x $70^{0.5}$	76.264 m^3

Table 7.2: Calculation of carbonation after demolition. Calculation of carbonation of all pre-cast concrete products produced in Denmark in 2003.

Step	Calculation	Example
1	Volume of PCP produced in Denmark in 2003 (4)	1.276.923 m^3
2	Percentage of concrete demolished after 70 years (year 2073)	80%
3	Percentage of concrete recycled as RCA (5)	90%
4	Volume of PCP that is processed to RCA by the year 2073, (steps1-3)	919.385 m^3
5	Average carbonation of PCP produced in Denmark in 2003 after a service life period of 70 years	27.4%
6	Volume of RCA not carbonated by the year 2073 = 919.385 m^3 x (100%-27.4%)	667.865 m^3
7	Percentage exposed below and above ground (5).	100% below ground
8	Particle size distribution of RCA in Denmark (5)	Table 7.3
9	Carbonation rate for buried concrete from **Fejl! Henvisningskilde ikke fundet.** (3)	0.00075 ($m/yr^{0.5}$)
10	Coefficient to account for the contribution to carbonation of 14% limestone present in CEM II A/L (3)	1.05
11	Modified carbonation rate (eq. 3)	0.00075 x 1.05 = 0.00079 ($m/yr^{0.5}$)
12	Volume carbonated after 5 years = Exposed area x carbonation rate x $yr^{0,5}$, Table 7.3 and Table 7.4	502.906 m^3

Table 7.3: Particle size distribution of RCA in Denmark (5)

Particle sizes	Percentage	m^3	Thickness (m)	Exposed area (m^2)
<1mm	21	140.252	0.001	841.510.283
1 -10mm	30	200.360	0.005	240.431.509
10-30mm	44	293.861	0.02	88.158.220
>30mm	5	33.393	0.05	4.007.192

Table 7.4: Volume of carbonated RCA after 5 years. The carbonation volumes written in bold imply that the whole size fraction has carbonated within 5 years.

Particle sizes	Percentage	Volume (m^3)	Volume carbonated after 5 years (m^3)
<1mm	21	140.252	**140.252**
1 -10mm	30	200.360	**200.360**
10-30mm	44	293.861	155.238
>30mm	5	33.393	7.056

7.3 Volume of carbonated concrete in the Nordic countries

The calculated carbonation of concrete produced in 1950 is presented in Figure 7.1 to Figure 7.4.

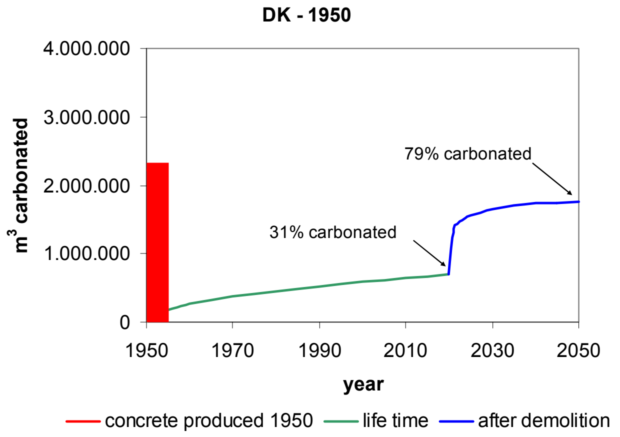


Figure 7.1: Carbonation of concrete in Denmark

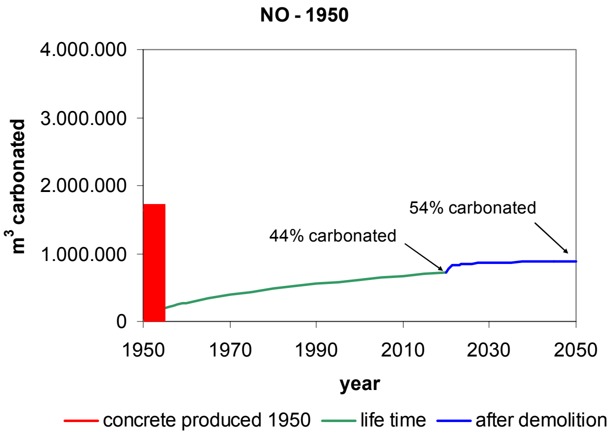


Figure 7.2: Carbonation of concrete in Norway

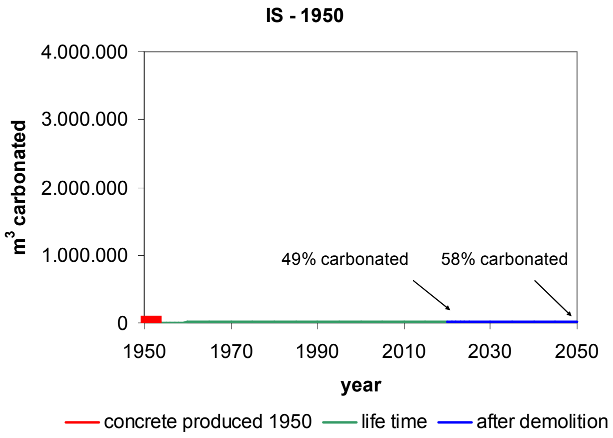


Figure 7.3: Carbonation of concrete in Iceland.

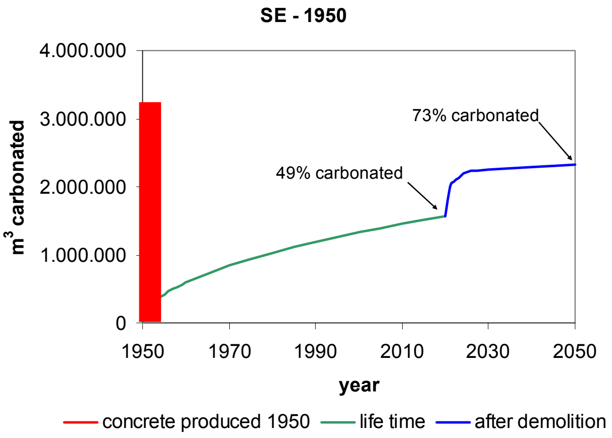


Figure 7.4: Carbonation of concrete in Sweden

There is a significant increase in carbonated volume after demolition (~year 2020) due to the higher exposed area of demolished concrete. This increase is more significant in countries with high percentage of recycled concrete. The carbonation of concrete produced in 2003 is presented in Figure 7.5 to Figure 7.8.

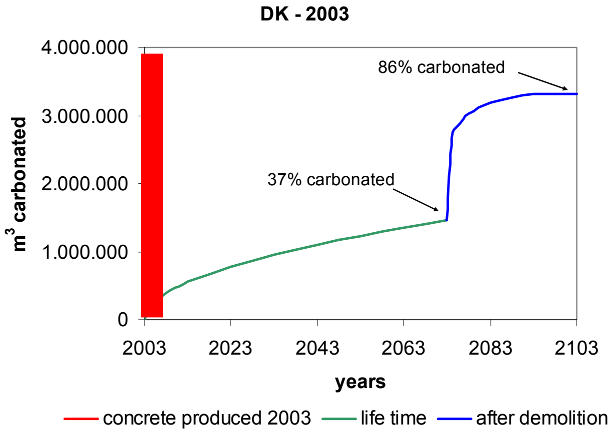


Figure 7.5: Carbonation of concrete in Denmark

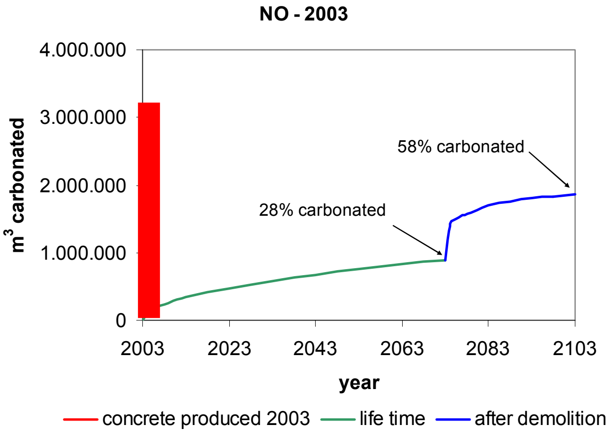


Figure 7.6: Carbonation of concrete in Norway

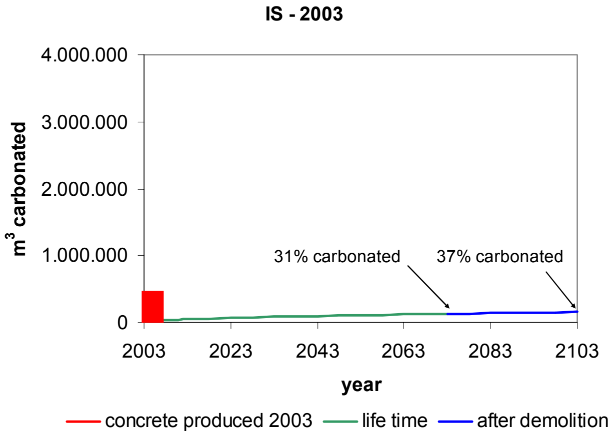


Figure 7.7: Carbonation of concrete in Iceland

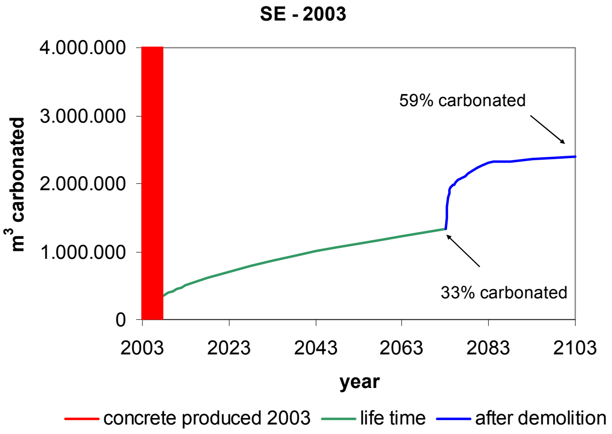


Figure 7.8: Carbonation of concrete in Sweden

Again, a significant increase in carbonated volume is observed after demolition. The high rate of carbonation in Denmark after demolition is due to the very high level of recycling in this country (90% of demolished concrete is recycled). The rates of carbonation as well as other assumptions used in these calculations are considered conservative. For example, the calculations only include carbonation of demolished and recycled concrete after service life, i.e. no carbonation for wet and buried concrete after 70 years. However, wet and buried concrete continue to carbonate after 70 years. Additionally, the rates of carbonation used (Table 5.1) do not include the effect of calcium leaching. The surface are of demolished concrete is calculated based on smooth spherical particles. However, the surface area of crushed concrete particles is larger than the one calculated due to their roughness and irregular shape. Therefore, the rate of carbonation of concrete in Nordic countries is probably higher than the values shown here. There is, however, a need to verify the actual carbonation rate of recycled concrete by measurements in the field.

7.4 CO_2 balance of concrete in the Nordic countries

Cement production is a minor contributor to CO_2 emissions in the Nordic countries. Table 7.5 shows the total CO_2 emission in the Nordic countries and the CO_2 emission due to cement production in each country. Cement production accounts for 3.2, 3.3 and 4.3% of the total CO_2 emission in Norway, Sweden and Denmark, respectively. The corresponding number for Iceland is 2.4%.

The amount of CO_2 emitted from cement production can be divided in CO_2 released by calcination of limestone and from fuel combustion, respectively. The total CO_2 emission from cement production given in Table 7.5 accounts for CO_2 from both sources. The emission of CO_2 due to calcination is also provided in Table 7.5 and accounts for about 60% of the total CO_2 emission (cf. section 3.2). As discussed in section 4, only CO_2 emitted from calcination is reabsorbed through concrete carbonation. Calculation of CO_2 uptake is based on the volume of carbonated concrete derived in section 7.3, and is calculated as described in section 7.1.

Table 7.5 reveals that about 25% of the CO_2 emitted in the calcination process will be reabsorbed in concrete in Denmark, Norway and Sweden by 100 years. The corresponding number for Iceland is 83%. The higher number for Iceland is due to fact that Iceland imports approximately 50% of its cement consumption. Therefore, its CO_2 uptake is the highest among the Nordic countries relative to the CO_2 emission from the national cement industry. The other Nordic countries export a significant amount of their cement production, and have a smaller percentage of import. The data in Table 7.5 shows that about 15% of the CO_2 emission from the Nordic cement industry, or about 0.5% of the total national emissions, for the year 2003 will be reabsorbed by carbonation of concrete in these countries in a 100 year perspective. The numbers for Iceland are higher, 42 and 1% respectively, due to the reasons mentioned previously.

Table 7.5: The CO_2 balance of concrete in the various Nordic countries, based on total cement production in the respective countries.

	Denmark (2003)	Norway (2003)	Sweden (2003)	Iceland (2003)
Total CO_2 emission (million metric tons)	58	43.2	57.6	2.2
Total CO_2 emission from cement production[i] (million metric tons)	2.5	1.4	1.9	0.06
CO_2 emission from the calcination process of cement production[i] (million metric tons)	1.3	0.9	1.1	0.028
Calculated CO_2 uptake (carbonation) after 100 years (million metric tons)	0.34	0.22	0.24	0.021
Percent of CO_2 taken up by carbonation compared to the CO_2 emitted in the calcinations process	26	24	22	75

[i] Total cement and clinker production

In Table 7.5 the CO_2 uptake from carbonation taking place in the Nordic countries was compared with the CO_2 emission from the total cement and clinker produced in this region. As the Nordic cement manufacturers export considerably more cement and clinker than is imported to the region, this approach underestimates the total CO_2 uptake by the cement produced in the Nordic countries. Obviously, concrete produced outside the Nordic countries with Nordic cement will also carbonate. In Table 7.6 this effect is accounted for by relating the CO_2 uptake in concrete to the cement consumption (rather than to the cement production). The cement consumption comprises domestic deliveries and import. It is assumed that the CO_2 emission for the production of one unit imported cement is the same as for one unit domestically produced cement. Note that , up to almost 60% of the CO_2 released by calcination is re-absorbed by concrete placed in Nordic countries.

Similar studies to the present one have been performed previously by Gajda and Miller (6) and by Jacobsen and Jahren (7). These authors arrived to considerably lower numbers for CO_2 uptake than obtained in the present report, most likely because they do not account for the CO_2 absorption after demolition.

Table 7.6: The CO_2 balance of concrete in the various Nordic countries, based on cement consumption in the respective countries.

	Denmark (2003)	Norway (2003)	Sweden (2003)	Iceland (2003)
Cement consumption compared to cement production (%)	43	75	64	177[1]
Total CO_2 emission related to production of the cement consumed (million metric tons)	1.13	1.05	1.21	0.11
CO_2 emission from the calcination process related to production of the cement consumed (million metric tons)	0.600	0.675	0.730	0.05
Calculated CO_2 uptake (carbonation) after 100 years (million metric tons)	0.34	0.22	0.24	0.02
Percent of CO_2 taken up by carbonation compared to the CO_2 emitted in the calcination process of the cement consumed	57	33	33	42

[1] Due to the large percentage of imported cement.

There are also differences in the total amount of CO_2 that can be absorbed by carbonated concrete between this study and Gajda and Miller (6). For example, Gajda and Miller (6) assume that only the CaO from $Ca(OH)_2$ will carbonate, whereas in the present work it is assumed that in addition to that half of the CaO in the C-S-H and half of the CaO in the AFt and AFm phases also will carbonate (3). The assumption made by Gajda and Miller imply that 100 metric tons of cement can absorb 19 metric tons CO_2, while the corresponding number for CO_2 uptake with our assumption (eq. 4) is 38 metric tons CO_2. This difference has a major effect on the calculated CO_2 uptake. Engelsen et al. (5) found from their experimental study that the assumption used by us (i.e. eq. 4) is reasonably correct. Additionally, the decrease in the content of calcium hydroxide available for carbonation in the presence of supplementary cementitious materials (e.g. fly ash and silica fume) were considered by Gajda and Miller, but were not accounted for in the present project (3). These effects accounts for most of the difference in the calculated numbers for CO_2 uptake obtained in the various studies.

8. Conclusions

Portland cement concrete absorbs appreciable amounts of CO_2 from the atmosphere during its lifecycle. In this report the amount of CO_2 taken up by concrete has been calculated. The CO_2 uptake process is called carbonation and implies that CO_2 from the atmosphere diffuse into the concrete and combine with CaO of the reacted cement to form limestone (i.e. $CaCO_3$), the same natural mineral Portland cement was made of. Carbonation is a relatively slow process. Our calculations are therefore based on carbonation during a 100 year period, assuming a 70 years service life period of concrete structures and a 30 year period of CO_2 uptake after demolition. Parts of the demolished concrete are processed to recycled concrete aggregates (RCA). The high surface area of RCA is assumed to increase the CO_2 uptake, and this effect is accounted for in the calculations of the CO_2 uptake. In a geological time frame all CO_2 released by the calcination process (i.e. the decomposition of limestone in cement manufacturing) will be re-absorbed by carbonation.

Over 100 years, one year of Nordic concrete construction is calculated to absorb 0.34, 0.22, 0.24 and 0.021 million metric tons of CO_2 in Denmark, Norway, Sweden and Iceland, respectively. This implies that about 0.5% of the total national CO_2 emissions will be re-absorbed in concrete in Denmark, Sweden and Norway. The corresponding number for Iceland is about 1%. The calculated CO_2 uptake implies that up to 57% of the CO_2 emitted due to calcination in the production of the Portland cement utilized in Nordic concrete construction will be re-absorbed by 100 years. Previous studies of CO_2 uptake have yielded considerably lower numbers for the total CO_2 uptake. One reason for this is that the previous studies assumed lower numbers for the specific CO_2 uptake pr unit reacted cement. Experimental studies undertaken in the current project indicate that the specific CO_2 uptake (38 metric ton CO_2 pr 100 metric ton reacted Portland clinker) used in the present report is justified (5).

The calculations are based on statistics regarding cement and concrete production and consumption volumes. Likewise, volumes of demolished concrete and recycled concrete aggregates are based on statistical data. Carbonation rate factors are largely based on measured values of concrete structures. These rate factors have been assumed for recycled aggregates as well. It is advised that carbonation rate factors are verified by further measurements for particularly high quality concrete, concrete water saturated or below ground, and recycled concrete aggregates.

9. References

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