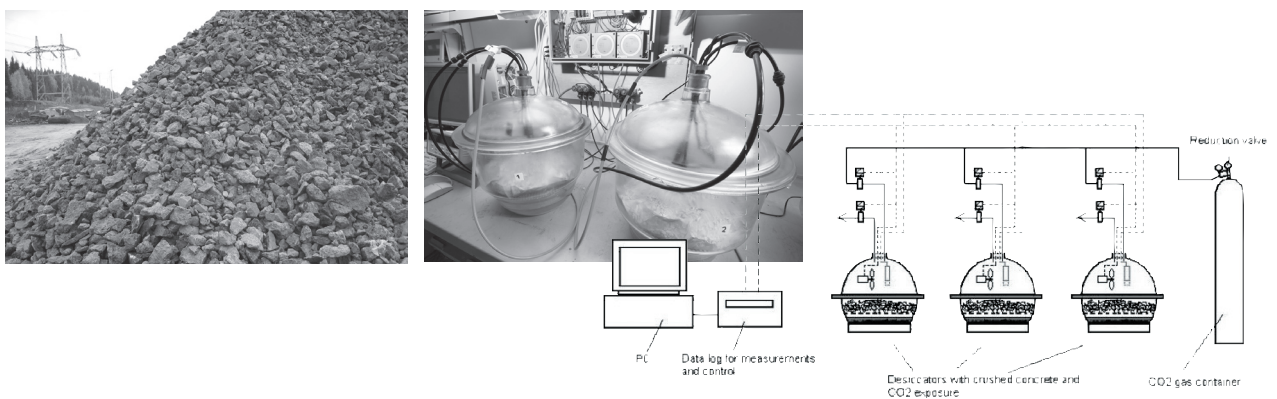Christian J. Engelsen, Jacob Mehus, Claus Pade and Dag Henning Sæther

Carbon dioxide uptake in demolished and crushed concrete

CO$_2$ Uptake During the Concrete Life Cycle
Nordic Innovation Centre Project 03018

BYGGFORSK
Norwegian Building Research Institute

Christian J. Engelsen, Jacob Mehus,
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Project report 395 – 2005

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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.

Summary

Recycled Concrete Aggregates (RCA) produced in the Nordic countries was summarized and its scenario applications with regard to the grain size were described. The CO_2 uptake to different crushed concrete types was then measured by conducting extensive accelerated laboratory tests, in order to document any differences in the uptake rate between the different crushed concrete samples. Furthermore, the maximum uptake of CO_2 within reasonable testing time in laboratory was also determined.

The annually volumes of concrete rubble generated in the Nordic countries, except for Island, was estimated to be in the range of 0.6 to 1.2 million ton. From these concrete rubble volumes, the production of RCA were calculated to be in the range of 0.2 to 1.0 million ton corresponding to a recycling level of 30-90 %. In Norway, Finland and Sweden the current recycling level is at 30, 50 and 60 % respectively. However, these countries reported that the target recycling level is 70 % by the end of 2010. The current recycling level in Denmark was reported to be 90 % and is expected to be the same by the end of 2010. In Finland, however, a major increase in the concrete rubble generation (from 45 % to 60 %) as well as the expected increase in the recycling level results in a major increase in the RCA production by the end of 2010. The annual concrete rubble generation in Island is approximately 50 000 ton which is landfilled.

In the laboratory different concrete mixes were tested for CO_2 uptake. After hardening the mixes were crushed into different grain sizes. It was found that 60-80 % of the CO_2 released released during calcination is reabsorbed to the concrete mixtures with w/c of 0.6 or higher for the grain size of 1-8 mm within 20-35 days of exposure. Furthermore, the calculation showed that 60-90 % of the total CaO in the same samples was carbonated. Determination of the total carbon in the carbonated samples by total combustion and CO_2 detection showed reasonable agreement with the measured CO_2 uptake.

The w/c ratio was found to be crucial as expected. Comparison of the mixes with the w/c ratios from 0.4 up to 0.75 showed large differences as the highest w/c ratio gave the highest carbonation rate. Thus, it was found that more than 90 % and less than 10 % of the CO_2 was absorbed within the first 50 hours of exposure for the mixes with w/c of 0.75 and 0.4 respectively testing samples with grain size of 1-8 mm. Coarser aggregate samples carbonated significantly slower.

Although the reaction kinetics varied due to the changing CO_2 partial pressure in the exposure desiccators, this test setup provided a fairly rapid quantification of the carbonation rate in between different concrete mixes. The tests also gave a realistic measurement of the total CO_2 uptake for the different samples which can support the documentation of concrete carbonation during service life and secondary use.

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1   Introduction

1.1   Objective

Carbonation of concrete is an environmental process in time. When concrete structures are demolished and refined to Recycled Concrete Aggregates (RCA) the surface area is largely increased. The CO_2 uptake rate per unit mass of concrete and thus the total amount of CO_2 uptake is therefore increased in the secondary life (after demolishing stage).

The task of this work was two folded. The first part was to summarize the produced RCA in the Nordic countries and describe its scenario applications with regard to the grain size. Based on these estimations and by applying different carbonation rates depending on different scenarios, the total CO_2 uptake by concrete in secondary life can be calculated

In the second part of the project the CO_2 uptake to different crushed concrete types was measured by conducting extensive accelerated laboratory tests. Test method and test setup was developed during the initial stage of the project. The objective of the testing was to document any differences in the uptake rate between the different crushed concrete samples. Furthermore, the objective was to identify the maximum amount of CO_2 uptake within reasonable testing time.

1.2   Background

Carbonation of concrete is a well known process where the carbon dioxide (CO_2) reacts with calcium hydroxide (CH) leading to the calcium carbonate ($CaCO_3$) precipitate. The reaction takes place in the aqueous phase i.e. in the pore water system, at concrete surfaces in contact with water or precipitation can occur away from a submerged concrete surface provided with water flowing conditions.

The source in the carbonation process is the natural CO_2 in the atmosphere with an average concentration of 0,035 volume %. Below ground the CO_2 concentration in deeper soil layer can increase up to 10 000-50 000 ppm by volume due to the degradation processes of organic matter in the soil (Appelo and Postma 1993).

1.2.1 Chemistry of carbonation

The detailed description of the concepts of the carbonation chemistry is well described elsewhere (Lagerblad 2005, Bary and Sellier 2004). However, some fundamental concepts will also be described in this section.

The carbonation reaction is taking place in the aqueous phase. Thus the atmospheric CO_2 must dissolve in water before it can react with CH to form calcium carbonate (CC). The chemical reactions in the carbonate system can be described in the following way:

$$CO_2(g) + H_2O = H_2CO_3 \tag{1}$$

$$H_2CO_3 = HCO_3^{2-} + H^+, \qquad pK_a = 6{,}35 \tag{2}$$

$$HCO_3^{2-} = CO_3^{2-} + H^+, \qquad pK_a = 10{,}33 \tag{3}$$
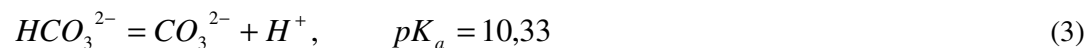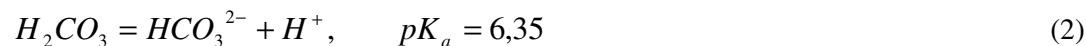
When CO_2 dissolves in water, the bicarbonate (HCO_3^-) or carbonate ion (CO_3^{2-}) will form dependent on the pH of the water according to reaction 2 and 3. In the case of pore water in concrete, HCO_{3^-} ions will be the major specie in carbonated zone (low pH) while the CO_3^{2-} ions will be present in the pore water in the uncarbonated cement paste (high pH). Intact cement paste pore water is often saturated

with calcium hydroxide (CH) and together with the alkali ions result in the high pH in concrete. The carbonation process can thus be described as follows:

$$CaOH_{(S)} <=> Ca^{2+}_{(aq)} + OH^-_{(aq)} \tag{4}$$

$$Ca^{2+}_{(aq)} + CO_3^{2-}_{(aq)} = CaCO_{3\ (S)} \tag{5}$$

As equation (5) continues, more portlandite (CH) will dissolve according to (4) in order to maintain the equilibrium and thus the pore water pH. When all the CH have been dissolved and precipitated as CC the calcium silicate hydrate (C-S-H) will release Ca ions in order to maintain the pH. With continuously access to CO_2, the C-S-H gel starts to dissolve and eventually the pH will decrease. At pH 11,6 and pH 10,6 the AFm and Aft will start to decompose respectively. When the phenolphthalein change occur at pH < 9,2 the Ca/Si ratio is approximately 0,85, and the C-S-H is transformed into silica gel (Lagerblad, 2005). The carbonation consumes Ca ions in the pore solution and this will be compensated by dissolution/release of Ca ions from the cement hydrate phases.

Equation (1)-(5) show that the transport mechanism of CO_2 consists of a diffusion process of carbonate species in the aqueous phase and also diffusion of CO_2 gas in the pore system (connective pores). The transport in the latter case is faster due to the gas diffusion but the carbonation reaction, however, needs free water. Thus, the CO_2 gas has to dissolve in the pore water before it can react with the calcium ions. This makes the carbonation process a coupled mechanism where the humidity and the porosity of uncarbonated and the carbonated layer in concrete determine the speed of carbonation. In a recent study of steel slag carbonation it was found that under certain conditions diffusion of Ca towards the surface of the particle most likely determine the overall reaction rate for this type of alkaline materials (Huijgen et al 2005).

1.2.2 Carbonation controlling factors

Humidity
Due to the coupled diffusion mechanism, humidity is one controlling factor. In concrete with water filled connective pores the transport mechanism is ion diffusion leading to slow carbonation. In dry concrete the CO_2 gas diffusion is fast but the lack of water also leads to slow carbonation. Thus, there will be a relative humidity (RH) optimum for optimal carbonation rate which is recognized to be in the RH range of 50-60 % (Gjerp and Oppsal, 1998).

Porosity
From the above it is obvious that porosity of the intact concrete is an important controlling factor, influencing on both mechanisms, the ion and gas diffusion of CO_2. In general a low water/binder ratio gives a low porosity which in turn gives slow carbonation. Also the porosity of the carbonated layer will determine the carbonation rate. In the latter the influence can be related to where in the pore system CC precipitates i.e. as minute crystals in the capillary system or on the surface of the hydrate phases. The first case will lead to decrease in the porosity (finer capillary system). This is typically the case in pure Portland cement paste where portlandite is the first to be carbonated. Decrease in porosity is also found to be more important with increasing w/c ratio (van Gerven et al 2004).

In cement paste with less CH, i.e. concrete with silica fume, GBFS or fly ash the precipitation may occur in the vicinity of the C-S-H thus affecting the gel porosity. This gives a coarser pore system in the carbonated layer that in turn increases the carbonation rate. The mode of precipitation is dependent on the diffusivity and the concentration gradient (chemical potential) of the carbonate- and calcium species. A detailed description of these mechanisms is found in Lagerblad (2005). However, evaluation of the capillary pore system of the tested samples in the present work is beyond the scope of this project.

Temperature
The carbonation process increases with increasing temperature. As aggregates used for unbound application under ground the temperature will be relatively low all the year. It can be expected that this will slow down the carbonation.

Binder content
In general the binder content in concrete with the same water cement ratio (w/c) will not affect the rate (as depth – however the amount of CO_2-uptake per unit time is different) in service life. However, for crushed concrete the fine particles tend to be cement paste particles. In general smaller grain sizes, i.e. 1-8 mm, contain more cement paste particles compared to a grain size of 8-16 mm when the material is crushed. This difference will be less for crushed concrete material originally produced with higher binder content.

Concrete quality
As mentioned earlier, low w/c ratio will slow down the carbonation due to the porosity. It is also assumed that the carbonated layer will be dense for low w/c concrete. Furthermore, the degree of hydration will affect the porosity. In climate with low RH one can expect low degree of hydration leading to a porous cement paste.

When crushing high strength concrete, the breakdown of aggregate grains (e.g. granite) will appear as well as breakdown of the cement paste. This will make a more even distribution of the cement paste when crushed into different grain sizes. More stone surfaces will give less surface for carbonation of cement paste.

Particle size
Carbonation rate will be faster after demolition compared to the service life of concrete due to the increased surface area of finer particles when calculated by weight. Thus, the rate will increase with decreasing grain size fraction, i.e. the grain size 1-8 mm will carbonate faster than 8-16 mm.

Partial pressure of CO_2
Increasing the partial pressure of CO_2 will increase the carbonation rate. Significant increase in the carbonation rate has been reported in some suburban areas with increased CO_2 partial pressure (Lagerblad, 2005). For secondary use, i.e. application of crushed concrete in road base or as backfill material in utility trenches, the differences in CO_2 pressure can be substantial. Degradation of organic matter will increase the CO_2 in soil, and the critical factor will be the access of CO_2 in terms of diffusion and exchange with the atmosphere in the specific application.

Effects of pozzolanas
Inorganic materials that harden in water mixed with calcium hydroxide (lime) is by definition a pozzolan (Hewlett 1998). This means that CH is consumed in the reaction that forms more C-S-H. Silica fume and fly ash is the most common types of artificial pozzolanas in the Nordic countries. Studies have shown somewhat increased carbonation rate for concrete with fly ash or silica fume. It is, however, difficult to make a proper comparison in the literature due to the different basis for the assessments.

Silica fume is a high reactive pozzolan and will be consuming CH from the hydration already at an early stage. Thus the eventually precipitation of CC will form a more porous carbonated layer that will enhance the diffusion of both gas and carbonate ion through this layer. On the other hand, concrete with silica fume is denser in which will compensate for the potential higher carbonation rate.

Outer environment
Besides the CO_2 pressure, crushed concrete is highly dependent on the application scenario, i.e. above or below ground. Today most applications are below ground in road base or as fill material in ditches and utility trenches. Applications can also be in the saturated zone. Under saturated conditions (below ground water table) the leaching of CH into ground water will enter as a significant process together

with conventional carbonation. In the leaching process dissolved CH will eventually react with carbonate ions but on a different place compared with the dissolution point of CH. To what extent the leaching process will occur depends on the groundwater speed and its chemistry. In the unsaturated zone the cycles of intermittent wetting will cause a combination of the two processes (Gervais et al 2004).

2 Experimental

Accelerated carbonation experiments have been conducted at Danish technological Institiue (DTI) and Norwegian Building Research Institute (NBI). The concrete samples were cast with cements from Aalborg Portland (DK-samples) and Norcem (N- samples). After minimum 90 days of hardening the samples were crushed and fractionated into the different grain sizes.

2.1 Sample preparations

2.1.1 Mix design and properties for Norwegian samples

The chosen samples covered the most applied concrete mixes used today and also the most likely to be used in the next 10-20 years. In Table 1 the different cast sample mixes are shown. The samples were cast the 16th and the 17th of December 2003.

Table 1 Mix design for the samples cast at Norcem including the strength development

Sample	Norcem type	Exposure and durability class[1]	Quantity kg/m³				w/c	Compressive strength / Mpa		
			Cement	silica	P	SSP 2000		2d	28d	90d
N1-210	Anlegg	SV40/MA/MF40	400	20	2,40		0.44	40	78	82
N2-211	STD-FA	NA/M60	325	20	-	130	0.60	23	52	68
N3-212	Industri	NA/M60	325	-	-	1.95	0.60	40	55	58
N4-213	Anlegg	NA/M60	325	16.3	-	1.14	0.60	27	60	64
N5-214	STD-FA	NA/M60	325	-	-	1.30	0.60	23	43	54
N6-69	STD-FA	LA/M90	264	-	-	2.64	0.75	12	25	31
N7-70	Industri	LA/M90	264	-	-	5.28	0.75	19	33	34

[1]Epxosure class SV40 is according to the Norwgian Public Road Authorities. MA & NA is according to old concrete specifications in NS 3420, now replaced by NS-EN 206-1 with M and MF.

All mixes were cast into steel moulds, generating cubes of 10x10x10 mm. The casting volume was 100 L, thus forming 33 cubes per mix. Demoulding was carried out the following day of the casting.

Fresh and hardened concrete properties were measured according to the EN standards (12350 and 12390) and included the following properties:
- Air content
- Slump & flow
- Density (fresh and harden)
- Water absorption
- Compressive strength

Granulated concrete properties measured according to the EN standards (933-1 and 1097-6) and the NT Build 437. The following properties were included:
- Particle distribution
- Particle density and water absorption
- Acid solubility

2.1.2 Mix design and properties for Danish samples

The concrete samples tested at DTI included some of the most used concrete types in Denmark today. Also, three "historic" samples cast in 1983 were obtained from Aalborg Portlands outdoor exposure site. The mix designs of the eight samples tested at DTI are shown in Table 2.

Samples DK-1, DK-2 and DK-5 originate from 100x100x400 mm prisms cast from concrete mixed at a ready mixed concrete plant as part of the Danish Green Concrete project (1998-2002). The prisms were cured in water for an unknown time, and then placed on a pallet inside the DTI laboratory. Prior to crushing the carbonated edges of the prisms determined by phenolphthalein was removed by a diamond saw.

Samples DK-3 and DK-4 originate from Ø150 mm cylinders cast in DTI laboratory in January 2004. The cylinders were cured under water until being crushed in May 2004.

Table 2 Mix design for the concrete samples tested at DTI. * - Perstorp bioash, ** - The standard cement contained 20-25% fly ash, *** - cylinder strength

Sample ID	Cement type	Quantity (kg/m3)						w/c	Compressive strength, 28 d (MPa)***
		Cement	Fly ash	Silica	P	SP	AEA		
DK-1	AaP Rapid	166	60	12	1.41	-	0.22	0.67	32
DK-2	AaP Rapid	168	60	13	1.97	-	0.37	0.70	32
DK-3	AaP Rapid	172	93	-	1.00	-	1.33	0.72	26
DK-4	AaP Rapid	279	52	17	2.10	1.40	0.87	0.41	54
DK-5	Slite Std/PK	194	79*	-	1.19	2.15	-	0.71	37
DK-Hist-1	AaP Standard	261	**	-	-	-	Yes	0.54	27
DK-Hist-2	AaP Standard	199	**	-	-	-	Yes	0.59	27
DK-Hist-3	AaP low alkali	340	-	-	-	-	Yes	0.42	40

2.1.3 Hardening of the samples

The Norwegian samples where placed in the climate chamber (20 ^{0}C and > 90 % humidity) at Norcem immediately after the casting. After demoulding the following day, the samples where placed in a water bath for 10 days before they were placed in the climate chamber again for 90 days.

The Danish samples included samples of age between 90 days and 20 years of age. The younger samples had all been cured for 28 days in water tank according to EN 12390, while the history of the 20 year old samples is described in Bager 2002.

2.1.4 Crushing procedure of Norwegian samples

The objective is to crush and store material for measurement of CO_2 absorption. A total of three 1 kg samples are needed for three parallel tests from each concrete mix and each particle distribution. Thus, a minimum of 6 kg crush material is needed for each concrete mix. The following procedure has been used:
1. Specimens are crushed in a three step process in the lab at Norcem
    a. Initial crushing of cubes (100 x 100 x 100 mm) in compressive strength test machine
    b. Manual crushing of pieces to big to fit in a jaw crusher
    c. Sieving using 16 mm sieve – pieces larger than 16 mm to be further crushed.
    d. Crushing in jaw crusher

2. The batch is split by sieve analysis aiming at splitting material in three groups
   a. Material < 1.0 mm (not expected to be used in the CO_2 testing)
   b. Material 1 – 8 mm – roughly 5 kg/batch
   c. Material 8 – 16 mm – roughly 5 kg/batch
3. The crushed material will be put in sealed containers as quickly as possible after crushing and splitting. The crushed material is packed in air-tight containers and nitrogen gas is blown in the container replacing the air, thus preventing any further carbonation prior to testing.

The samples were crushed at Norcem in the April of 2004 and were transported the same day of fractionation to the laboratory of NBI.

2.1.5 Crushing procedure of Danish samples

a.   Initial crushing of cylinder in compressive strength test machine
b.   Manual crushing of pieces to big to fit in a jaw crusher
c.   Crushing in jaw crusher
d.   Manual sieving using 16 mm sieve
e.   The pieces larger than 16 mm is crushed in jaw crusher
f.   The crushed concrete sieved manually on an 8 mm sieve, subsequently on an 1 mm sieve splitting the crushed material into three fraction – 8-16 mm, 1-8 mm and 0-1 mm.
g.   Each fraction was stored in air tight containers until testing.

The samples were crushed in May 2004

2.2   CO$_2$ measurement

2.2.1 Principle of the method

Test portions were placed in desiccators specially built for this test application. The desiccators were filled with CO_2 gas until the concentration was 35000 ppm and the decrease in the concentration of CO_2 as function of time equalled the CO_2 uptake. Once the concentration was under a certain level (3500 ppm), the desiccator was refilled to 35000 ppm CO_2.

The measuring procedure, including CO_2 detection was conducted automatically while the refilling with CO_2 was done either automatically or manually (at DTI). Three replicate samples were used in most of the experiments. The testing was conducted in parallel at Norwegian Building Research Institute and Danish Technological Institute.

2.2.2 Test setup/apparatus and procedure

The test setup and test procedure were developed at NBI during the first stage of the project. Furthermore, the software used in the fully automated test rig at NBI was written in Visual Basic by Øyvind Sæther, NBI.

The same test principle was used at DTI with some minor deviations due to practical reasons see paragraph 2.2.2.5.

2.2.2.1   Equipment

The following equipment is needed for the test setup:

- Glass desiccators (or equivalent airtight test containers) with airtight connections for measuring equipment.
- Tubes for CO_2-gass for refill and pressure equalizing
- Tank with pressurized CO_2-gas
- Magnetic valves for PC controlled refill of CO_2-gas and for equalizing pressure during CO_2 refill.
- Fans for mixing of CO_2-gas in the desiccators
- Magnesium-nitrate for RH control
- Granulated concrete test material prepared according to 3.
- Data acquisition unit
- Computer
- Computer program designed to regulate the carbonation concentration and record measurement
- Metal gratings
- CO_2 transmitters for recording CO_2 concentration inside the desiccators (Vaisala GMT220 series 0 – 50000 volume-ppm or equivalent)

The main principles of the test setup are shown in Figures 1-3.

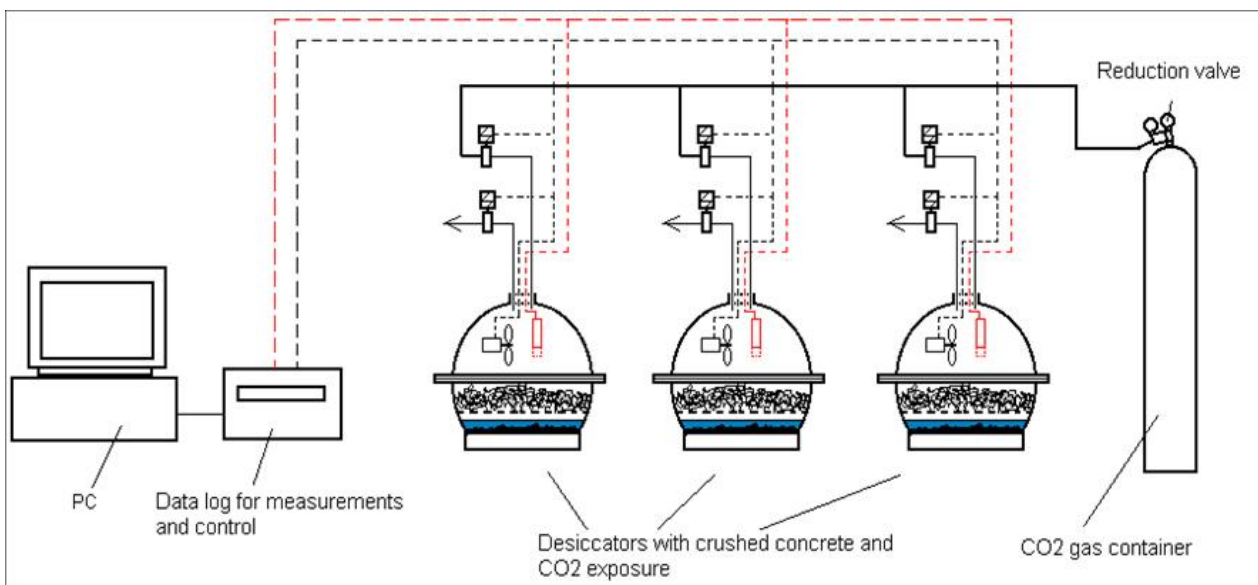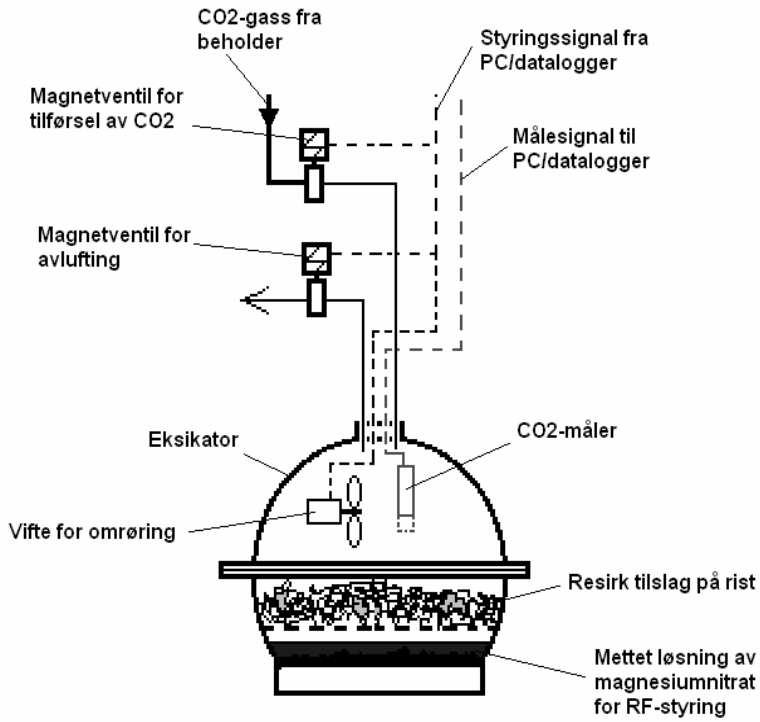Figure 1 Main principle for test setup with three desiccators

Figure 2 Detailed test setup of desiccator
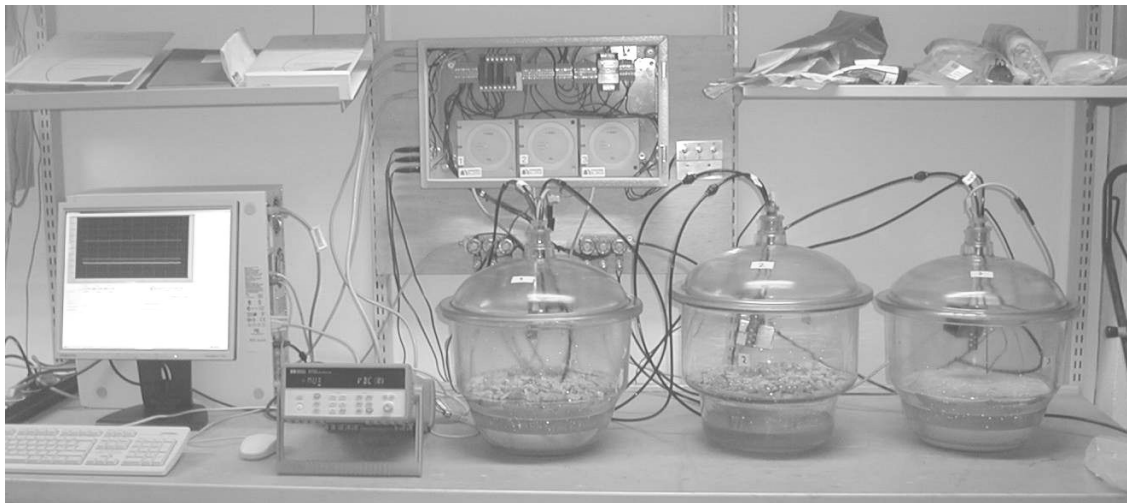
Figure 3 Overview of test setup in the NBI laboratory

2.2.2.2   *Exposure conditions*

Exposure conditions during CO_2 uptake should be:
- Relative humidity (RH) inside the desiccator between 50 – 60 % (using a saturated magnesium-nitrate solution to maintain a steady RH-level)
- Temperature of 21 °C ± 3 °C.

- CO_2 concentration inside the desiccator with a lower limit of approximately 3500 ppm and an upper limit of approximately 35000 ppm (ppm measured by volume). The actual concentration level is recorded during testing.

2.2.2.3 Execution

The granulated concrete test specimens are exposed to CO_2 absorption according to the following step by step procedure:

1. A saturated solution with 0,50 kg of water and 1,50 kg of magnesium-nitrate is placed at the bottom of each desiccator. Thus, providing a saturated magnesium-nitrate solution yielding a balanced RH level of 50-60 % in the desiccators.
2. The granulated concrete test material, 50 g/pr liter effective gas-volume, is placed on metal gratings above the magnesium-nitrate solution. The openings of the metal grating should not allow the test material passing through.
3. The desiccator lid is coated with a sealing agent to ensure a airtight seal and the lid is put in place.
4. The computer programme controlling the test set up is started in Region-1 of the test cycle, filling the desiccators with CO_2-gas (see Figure 4). The regulator for the CO_2-gas tank should be kept at a steady pressure (0,15 – 0,35 bar). If the CO_2-gas flow from the tank is to high this could cause air leaks in the desiccator, or the maximum CO_2-concentration significantly overshooting the target of 35000 ppm.
5. The test is terminated when the granulated concrete is fully carbonated.
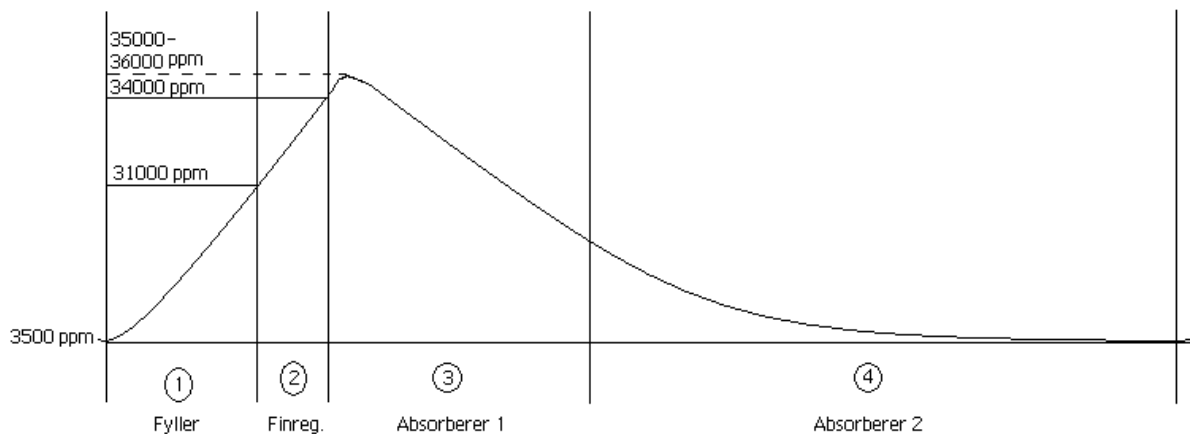
Figure 4 CO_2 absorption test cycle with: Region-1 = filling of CO_2-gas, Region-2 = fine-tuning of CO_2-level, Regions 3 and 4 = CO_2-absorption. The cycle is repeated until the material is fully carbonated.

2.2.2.4 Measurements

The following measurement and properties should be recorded:
- Weight of the granulated concrete specimen in each desiccator before CO_2-exposure
- CO_2-concentration is measured every 3 seconds and an average is calculated and written to a file with intervals of 30 second, together with the date and time of measurement.
- Weight of the granulated concrete specimen in each desiccator after CO_2-exposure

2.2.2.5   Minor deviation from the test procedure

The same principle of test set up as in Figure 1 was used at DTI. 500.0 g of crushed concrete is placed on a old sieve of mesh finer than 1 mm. 3.5% (-+ 0.2 %) CO_2 is led into the desiccator until the concentration is about 35000 ppm. The concentration of CO_2 is recorded every 3 minutes using Vaisala probes (two max 5 % and one max 15 %) placed at the top of the desiccators. The desiccators were refilled with CO_2 when the concentration was low or when it was convenient for the technician (during vacation periods the concentration could be low for several days). The calculation of CO_2-uptake was performed based on max and min concentration for each period between refillings. The total CO_2-uptake was calculated as the summation of CO_2-uptake in each period.

2.2.3 Handling of the samples after CO_2 exposure

After termination of the tests a sieve analysis was performed on the crushed concrete to give the particle size distribution. Finally, the crushed concrete was crushed finely and the insoluble residue was determined according to NT Build 437 and "DS/EN 1744 1.7" - i.e. according a tradition chloride analysis with digestion in nitric acid. Insoluble residue was calculated as mass of the residue on the filter divided by the original sample mass. The paste content is 1 minus the insoluble residue.

2.3   Carbon analysis

In order to calculate total calcium carbonate differently from the CO_2 uptake, determination of total carbon in the carbonated samples was conducted at Norcem A.S. The method used was IR-spectrometry using a LECO IR 344 according to the laboratory procedure 9C-KA03 in Norcem.

3 Results and discussion

3.1 C&D waste data in the Nordic countries

The objective of this task was to estimate the volume of Recycled Concrete Aggregates (RCA) derived from the volume of concrete rubble and the most applied scenarios for the this material. This also includes assessing the most likely grain sizes to be used in the different scenarios. The volume of concrete rubble had to be estimated from the Construction and Demolition waste (C&D waste) data in the different Nordic countries. These data are obtained from the following different sources:

- Norway: Statistics Norway (www.ssb.no) : Waste data for C&D industry for 1998 and 2001
- Denmark: Affaldstatistik 2002, Miljøstyrelsen and communication with Per Arevad, RGS90 (producer of crushed concrete)
- Sweden: Concrete recycling report 2002, confidential report within Heidelberg Cement
- Iceland: Edda Lilja Sveinsdóttir, et al. (2002). Construction and demolition waste in Iceland. Part 1: Classification and quantity. IBRI report 02-03.
- Finland: Perälä & Nippala:Construction wastes and their utilization VTT research notes.1936. Espoo 1998. 67 p,+ app. 20 p. in Finnish (corrected on the basis of construction volume) and Recycling of concrete and concrete slurry in the concrete industry. Confederation of Finnish Construction Industries RT. 2002. 33 p. + app. 7 p.In Finnish.

The results from the C&D waste data collection is shown in detail in appendix 6.1-6.5. Based on the sources above, the collected Nordic data are divided into the following different scenarios with regard to RCA:

- Bound application (as aggregate in new concrete etc.)
- Unbound application above ground (as road surface, landfilled etc)
- Unbound application below ground (as road base, backfill etc.)

For unbound applications the chosen grain size intervals are < 1 mm, 1-10 mm, 10-30 mm and > 30 mm. The results are summarized in Table 3.

Table 3 Concrete rubble, RCA and applications in the Nordic Countries in 2004.

Country	Concrete rubble 10^3 ton	RCA	RCA unbound application %		RCA bound application %
			Below ground	Above ground	
Norway	650-975	195-293	94	5	1
Denmark	800-1200	720-1080	100	0	0
Sweden	1080-1200	648-720	92	5	3
Iceland[1]	52	0	0	0	0
Finland	630-720	315-360	87	3	10

[1]Concrete is landfilled

The C&D waste data collected in the Nordic countries are subjected to some uncertainties due to the difficulties to monitor the exact volume of concrete rubble generated and the following share that is further processed to RCA. Thus, to give realistic estimates, the inquiry for each country was to deliver high and low estimates of the C&D waste generated based on their available literature sources. The data in Table 3 are thus reflecting these ranges of estimates.

Furthermore, the collection of data in the Nordic countries included also estimations of C&D waste approximately generated and also the recycling percentage of concrete rubble by 2010. Such kind of data is obviously related to uncertainties. However, the reported data indicated that the level of C&D waste generated by 2010 is anticipated to be almost the same as the current level. The exception was Island due to difficulties in obtaining data that could support this future estimation. Finland reported a slight increase of C&D waste but also a major increase of concrete rubble generation (45% - 60%).

The recycling level by 2010, however, was reported to increase in Sweden, Finland and Norway as shown in Table 4, including high and low estimates. The numbers from Norway was made according to Norwegian C&D Industry waste management plan.

Table 4 Recycling level with regard to concrete rubble currently and by 2010

Country	Recycling of concrete rubble 2003		Recycling of concrete rubble 2010	
	RCA produced 10^3 ton	Recycling %	RCA produced 10^3 ton	Recycling %
Norway	195-293	30	455-683	70
Denmark	720-1080	90	720-1080	90
Sweden	648-720	60	756-840	70
Iceland[1]	0	0	0	0
Finland	315-360	50	630-714	70

[1]Concrete rubble is landfilled

To be able to use the obtained Nordic RCA data for calculation of the CO_2 uptake, the grain size distribution has to be estimated. This have been reported as different grain sizes within the annually production of RCA as shown in Table 5.

Table 5 Distribution of different grain sizes in weight % of annually production of RCA

Country	Grain size / mm			
	% < 1	% 1-10	% 10-30	% > 30
Norway	10	25	20	45
Denmark	21	30	44	5
Sweden	10	25	40	25
Iceland[1]	10	0	0	90
Finland	10	24	40	26

[1]Concrete rubble is landfilled

3.2 CO$_2$ uptake

The carbonation process transfers the Ca species into $CaCO_3$ (CC). The reaction process takes place solely in aqueous phase (pore water) under normal CO_2 partial pressure conditions, i.e. reaction of Ca ion (Ca^{2+}) with the carbonate ion (CO_3^{2-}). In theory all of the Ca species can be decomposed to form CC. However, in the carbonated zone as indicated by phenolphthalein the CaO/SiO_2 is less than 0.8 (Chen et al 2004). Based on this and the estimation from Taylor (1997) that in cement paste with 65 weight % CaO, approximately 30 weight % is bound to the CSH (calcium silicate hydrates), a total of 25 % CaO is likely to remain uncarbonated.

3.2.1 Max CO$_2$ uptake in laboratory

Table 6 shows the results achieved in the laboratory experiments. It was found that for an exposure time in laboratory of 20-35 days, 60-80 % of the CO_2 released during calcination is reabsorbed for the concrete mixtures with w/c of 0.6 or higher. For the mixture with w/c of 0.4, the uptake amount was significant lower for the same exposure time.

Furthermore, the CO_2 uptake amounts in Table 6 show that the carbonated portion of CaO can be as large as 75 % of the total CaO as the estimations carried out by Taylor (1997) showed.

For the Norwegian concrete samples tested at NBI (N-samples) it is assumed that the Norcem Anlegg cement and Norcem Industri cement contain 91 weight % clinker, i.e. correcting for the content of

gypsum, limetone filler and iron sulphate. Furthermore, the fly ash cement, Norcem STD FA cement, contains 78 weight % clinker thus adjusting for the fly ash (18 weight %) and the gypsum content.

For the samples tested at DTI (DK-samples) it is assumed that the Aalborg Portland Rapidcement contained 93 weight % clinker, the Aalborg Portland "Low alkali" cement contained 97%-wt clinker, and that the Aalborg Portland Standardcement contained 75 weight % clinker.

Table 6 CO_2 uptake for different concrete mixtures exposed for 20-64 days, fraction 1-8 mm.

Concrete mixture	Exposure time days	W/C	CO_2 uptake		
			g/kg cement clinker	% of calcinations release	% of total CaO
N1-210	64	0.44	277[1]	61	54
DK-4	35	0.41	196	38	32
DK-hist-3	35	0.42	140	–	27
DK-hist-1	35	0.54	308	–	60
DK-hist-2	35	0.59	292	–	57
N2-211	22	0.60	339	88	83
N3-212	22	0.60	364	81	71
N4-213	22	0.60	341	76	67
N5-214	22	0.60	277	72	68
DK-1	20	0.67	256	–	50
DK-2	35	0.70	393	–	77
DK-3	30	0.72	417	80	89
N6-69	22	0.75	384	66	75
N7-70	22	0.75	299	66	59

[1] CO_2 uptake after 22 days exposure was 162 g CO_2 / kg cement clinker
⁻ Not calculated

Coarser concrete particles are expected to carbonate slower. This was also found in the carbonation experiments with the particle size 8-16 mm, shown in Table 7. All the samples obtained significant lower carbonation uptake amounts than the correspondent samples with lower particle sizes. The w/c ratio plays a major role in the carbonation process as recognised in paragraph 1.2.2. The carbonation rate will generally decrease with decreasing w/c ratio. This can also be seen in Table 7, as there are significant differences between the low w/c ratio sample (DK-4) and the other samples.

Table 7 CO_2 uptake for different concrete mixtures, fraction 8-16 mm.

Concrete mixture	Exposure time days	W/C	CO_2 uptake		
			g/kg cement clinker	% of calcinations release	% of total CaO
DK 4	23	0.41	68	–	13
N3-212	22	0.60	182	40	36
DK-1	23	0.67	144	–	28
DK-2	35	0.70	250	–	49
DK-5	23	0.71	153	–	30
DK-3	35	0.72	346	–	68

⁻ Not calculated

3.2.2 CO_2 uptake rates

Due to different concrete qualities the carbonation rate was expected to be different as well. Figure 5 shows the carbonation as function of exposure time for the different concrete samples. As expected, the figure shows that the carbonation rate is significantly higher for mixtures with high w/c. It can also be seen that the speed slows down after 10-15 days of exposure, except for the mixtures with w/c of 0.4.

Furthermore, the shape of the curves is different as the slope of the curves for the first 10-20 hours of exposure is proportional with the w/c ratio. Thus, the highest uptake rate during the first day of exposure can be seen for the mixture N6-69 and N7-70 in Figure 5c. These curves show that the available amount of CaO for carbonation is quickly reached compared with the other concrete mixes. The uptake rate for the DK-3 mix in the same figure is significant lower than the other samples with high w/c ratio. However, manual CO_2 refilling of the desiccators was applied in the experiments for the Danish concrete samples (see paragraph 2.2.2.5). As the uptake rates for this high w/c ratio samples can be faster than the manual CO_2 refilling interval, the experimental procedure can explain the unexpected low CO_2 uptake rate for DK-3.

Qualitatively, N6-69 and N7-70 show very consistent behaviour as the curves are almost similar. The CO_2 uptake for these mixes, however, slows down at different levels. This can be explained by uncertainties in the determination and the calculation of the cement clinker content in addition to the fact that N6-69 and N7-70 are concrete mixes of a Portland and a fly ash cement respectively.

For the concrete samples in Figure 5b (w/c 0.6), the CO_2 uptake curves are less steep than for the samples of higher w/c ratio. In the same figure it can also be seen that the samples N2-211 and N5-214 (both concrete with fly ash cement) show different carbonation behaviour. In the former sample, however, 6 % silica fume was added but it will require further testing to explain the influence of such an addition to the mix.

The concrete samples with the lowest w/c ratio tested in this project are shown in Figure 5a. As pointed out earlier, the lowest CO_2 uptake rates were achieved for these samples as can be seen from the steepness of the curves in the figure. Furthermore, the samples DK-4 and N1-210 (both with w/c of 0.4) that are conducted with manual and automatic refill of CO_2 respectively in the laboratory, show relatively good agreements.
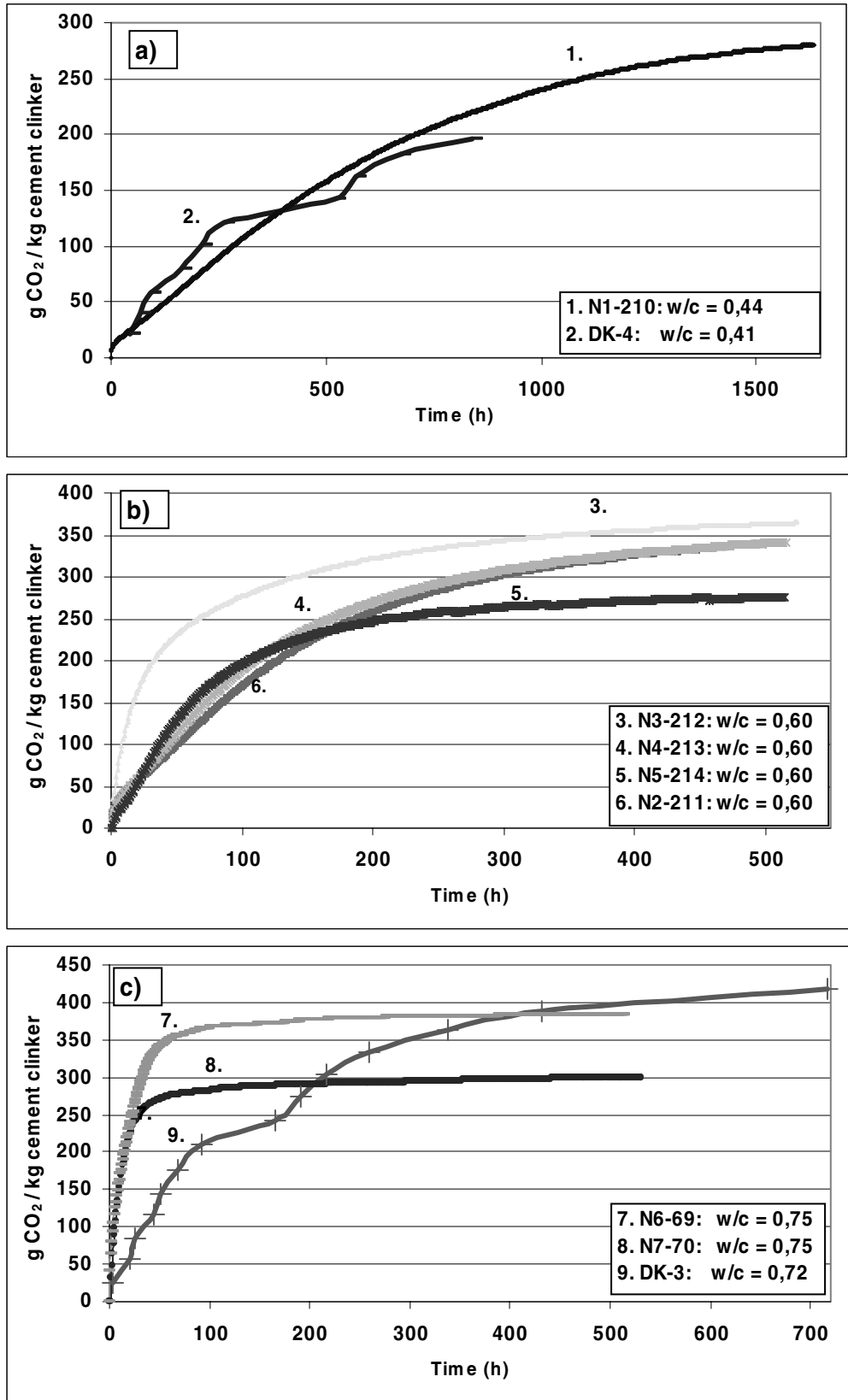
Figure 5 Carbonation as function of time for different concrete mixtures of grain sizes 1-8 mm and different w/c ratios.

3.2.3 Carbonation mode

The experiment conducted in this project can not assess potential different modes of carbonation. In Figure 5, however, N6-69 and N7-70 most likely show a different carbonation pattern than the rest of the concrete mixes. The CO_2 has to be transported through its own alteration product and the transport rate will thus depend on the porosity of the carbonated zone which in turn depends on the precipitation mode of calcite. Thus, if $CaCO_3$ precipitates as minute crystals in the capillary pore system, as in the cases of $Ca(OH)_2$ rich cement pastes (CEM I), the carbonation results in a densification (decrease in porosity) of the altered layer. This will slow down the transport velocity and hence the carbonation rate.

Contrary, for more porous concrete, i.e. higher w/c ratio and/or $CaCO_3$ precipitation close to the C-S-H, the transport of CO_2 is faster and results in higher carbonation rates.

If the transport of CO_2 is faster than the dissolution to carbonate ions and the following reaction to form $CaCO_3$, the results will be a double carbonation front due to not fast enough consumption of CO_3^{2-} ions (Lagerblad, 2005). The concrete samples N6-69 and N7-70 could follow the high transport mode due to the high w/c ratios and the fact that the tests are conducted under accelerated conditions. Furthermore, the carbonation rate slows down at levels that most likely show that the CO_2 diffusion has achieved a significant depth of the particles. Table 6 shows that 60 and 80 % of total CaO is carbonated within relatively short exposure time for N7-70 and N6-69 respectively. Thus, all parts of the particles are more or less carbonated due to easy access of CO_2 and the rate slows down rapidly as soon as virtually all the available CaO is carbonated. This rapid deacceleration is most likely not possible to achieve under conventional diffusion controlled carbonation, because the alteration product is different.

3.2.4 Particle size effect

In order to illustrate the effect of particle size on carbonation rate, 3 different particle size fractions of concrete mix N3-212 were tested. This is a concrete with Portland cement (CEM I). The following fractions were tested:

- < 1 mm
- 1-8 mm
- 8-16 mm

During the first few hours of exposure the test sample with the smallest particle size (< 1 mm) achieved the highest carbonation rate as illustrated in Figure 6. However, after approximately 5-10 hours of exposure the CO_2 uptake slows down more rapidly than the 1-8 mm sample. If the uptake level is taken into account, this unexpected behaviour seemed to appear due to a thin carbonation layer formed that sealed off the pulverised sample, which was spread out in a 10-20 mm layer on the screen in the desiccator (see Figure 3).

Furthermore, the carbonation of the N3-212 sample (< 1 mm) was also compared with the carbonation for the N6-69 sample (1-8 mm) as shown in Figure 6. The comparison was made to he N6-69 sample due to the fact that this sample contains the same cement type (CEM I) as N3-212 sample (< 1 mm) and also because of the high CO_2 uptake rate measured. The comparison showed a significantly different carbonation rate for these two samples although the rate appeared to be quite similar over the first few hours (see Figure 6). This distinct deviation also indicates that a thin carbonation layer is rapidly formed for the pulverized sample (<1 mm).
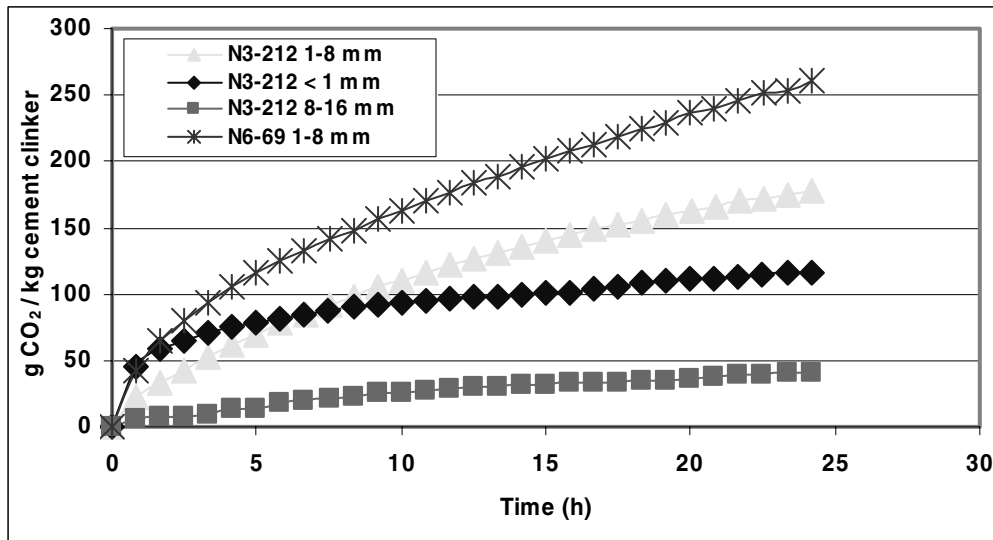
Figure 6 Carbonation as function of time for different grain sizes

3.2.5 Carbon analysis

Total carbon in the exposed samples were analysed as a control procedure for the N-samples. The carbon analyser determines the total carbon in the sample by combustion and CO_2 detection. Carbon contribution from the organic admixtures will thus be present in the analytical results. Table 8 shows the determined carbon in weight % and the equivalent amount of CO_2 in the samples, thus assuming stoichiometric condition and all CO_2 originate from $CaCO_3$ in the paste. The results showed in all samples higher values when the samples are analysed by the carbon analyser. The deviations, however, were less than 40 %. The fact that the total carbon is analysed, this results are in reasonable agreement with the measured values in the CO_2 test rig.

Table 8 CO_2 uptake compared with the carbon analysis

Sample	Carbon analyser Weight % of C	Equivalent amount of CO_2 uptake g/kg	Uptake from test rig g/kg	Difference %
N1-210	1.28	288	277	4
N2-211	1.20	397	339	17
N3-212	1.45	417	364	15
N4-213	1.46	436	341	28
N5-214	1.29	379	277	37

3.2.6 Limiting factors and field experiments

Carbonation is a time dependent environmental process. The CO_2 uptake rate under normal conditions is rather slow in the context of conducting laboratory experiments within the time frame of the project. Due to this fact, optimum moisture conditions were used (55-60%), and the CO_2 concentration was operated in the range 3500-35000 ppm, 10-100 times concentration in the atmosphere. The latter parameter will affect the carbonation mode since $CaCO_3$ will most likely precipitate on different places when compared with normal CO_2 pressure conditions. Furthermore, the reaction kinetics varies due to the changing partial pressure in the desiccators.

However, the accelerated conditions were computer controlled for all samples (N-samples) and the tests where carried out in 3 replicates (N-samples). The relative standard deviations achieved for the three parallel samples did not exceed 5 % for any of the concrete mixes or particle sizes. Consequently, to assess the carbonation rate in between the different concrete mixtures, this test setup provides a fairly rapid indication of the CO_2 uptake rate. The tests also give a realistic measurement of the total CO_2 uptake for the different samples.

In order to correlate the results obtained in these experiments into real life situations, one must define the scenario application as given in section 3.1. In more exact calculations, information concerning metrological and geochemical conditions should also be included. In applications above ground, the crucial factors determining the carbonation rate will be the local precipitation and temperature. For scenarios under ground one has to distinguish between applications above and below the ground water table. In the latter case the important factor will be the ground water chemistry and the ground water speed. In the unsaturated zone (above ground water table) parameters like infiltration rate and soil type are also important. Due to degradation of organic matter the CO_2 partial pressure will increase. Furthermore, intermittent wetting cycles can increase the leaching of CH.

Given the fact that the test conditions were similar and fully controlled for all samples in the laboratory experiments, the results obtained will make a sound base for potential field experiments which is a demand for correlating the obtained laboratory results. In scenarios with high infiltration, e.g. in utility trenches, the leaching/dissolution processes are of large importance and are expected to proceed relatively fast. In road base, however, the carbonation is more dependent on the access to CO_2/CO_3^{2-}.

In Norway full scale investigation with regard to leaching of minor constituents and major oxides from crushed concrete is ongoing through the Norwegian Roads Recycling Program (Petkovic et al 2004).

4   Conclusion

According to the Nordic recycling data collected, the annually generation of concrete rubble was estimated to be between 0.6-1.2 million ton in the Nordic countries except Iceland which annually generates 0.05 million ton. Furthermore, current recycling levels are 30-90 %. Hence, significant amounts of CO_2 are being or have the potential to be reabsorbed to the crushed concrete in secondary life. The recycling is expected to increase in countries with low recycling level today, e.g. Norway, which in turn will affect the CO_2 uptake significant.

The experimental work conducted in laboratory verified the potential for CO_2 uptake in the crushed concrete. It was shown that the concrete quality, in terms of original w/c ratio, had large impact on the uptake rate. Furthermore, smaller particle sizes carbonates faster than larger particles due to increased reactive surface.

It was further found that a part of the CaO in the cement clinker is most likely to be uncarbonated. According to the literature, approximately 75 % of the total CaO in the clinker is carbonated, i.e. when the change in colour occur by the phenolphthalein test. The results obtained from the laboratory in this project showed 50-60 % and 60-90 % carbonation of total CaO for concrete samples with middle and high w/c ratios respectively. Based on these results, 75 % (of total CaO) is most likely a realistic level of carbonation to be taken into consideration when estimates of the total uptake of CO_2 to crushed concrete in reasonable time scale (20-50 years) is to be calculated.

Due to accelerated conditions different carbonation patterns most likely were observed.

5   Litterature

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6   Appendix

6.1   Construction and demolition waste data in Norway

C&D-waste data for Norway:			
Population:		4 500 000	
Survey completed by:		Jacob Mehus (NBI)	
Date:		28.04.2004	
Current situation:		**Weight (ton)**	**(% by weight)**
C&D waste generated annually (ton):	High estimate:	1 500 000	
	Low estimate:	1 000 000	
Waste by population (based on high estimate)		0,333	
Concrete rubble (% of total C&D-waste)			65 %
Concrete rubble generated annually (ton):	High estimate:	975 000	
	Low estimate:	650 000	
Concrete recycling level (% of rubble generated)			30 %
Annual production of recycled concrete aggregate (RCA)	High estimate:	292 500	
	Low estimate:	195 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			1 %
Unbound application below ground (as road base, backfill etc.)			94 %
Unbound application above ground (as road surface etc.)			5 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	2 925	
	Low estimate:	1 950	
Unbound application below ground (as road base, backfill etc.)	High estimate:	274 950	
	Low estimate:	183 300	
Unbound application above ground (as road surface etc.)	High estimate:	14 625	
	Low estimate:	9 750	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			10 %
1 - 10 mm			25 %
10 - 30 mm			20 %
> 30 mm			45 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	29 250	
	Low estimate:	19 500	
1 - 10 mm	High estimate:	73 125	
	Low estimate:	48 750	
10 - 30 mm	High estimate:	58 500	
	Low estimate:	39 000	
> 30 mm	High estimate:	131 625	
	Low estimate:	87 750	
References: Current waste data for Norway are based on:	Statistics Norway (www.ssb.no) : Waste data for C&D industry for 1998 and 2001		
	Personal experience from several projects related to C&D-waste and recycled aggregate		

Future situation approx. by 2010	Weight (ton)		(% by weight)
C&D waste generated annually (ton):	High estimate:	1 500 000	
	Low estimate:	1 000 000	
Waste by population (based on high estimate)		0,333	
Concrete rubble (% of total C&D-waste)			65 %
Concrete rubble generated annually (tons):	High estimate:	975 000	
	Low estimate:	650 000	
Concrete recycling level (% of rubble generated)			70 %
Annual production of RCA	High estimate:	682 500	
	Low estimate:	455 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			1 %
Unbound application below ground (as road base, backfill etc.)			94 %
Unbound application above ground (as road surface etc.)			5 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	6 825	
	Low estimate:	4 550	
Unbound application below ground (as road base, backfill etc.)	High estimate:	641 550	
	Low estimate:	427 700	
Unbound application above ground (as road surface etc.)	High estimate:	34 125	
	Low estimate:	22 750	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			10 %
1 - 10 mm			25 %
10 - 30 mm			20 %
> 30 mm			45 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	68 250	
	Low estimate:	45 500	
1 - 10 mm	High estimate:	170 625	
	Low estimate:	113 750	
10 - 30 mm	High estimate:	136 500	
	Low estimate:	91 000	
> 30 mm	High estimate:	307 125	
	Low estimate:	204 750	
References: Future waste data for Norway are based on:	Statistics Norway: Waste data for C&D industry for 1998 and 2001		
	Personal experience from several projects related to C&D-waste and recycled aggregate		
	Norwegian C&D-industry waste management plan		

6.2 Construction and demolition waste data in Denmark

C&D-waste data for Denmark:			
Population:		5 400 000	
Survey completed by:		Claus Pade (DTI)	
Date:		18.05.2004	
Current situation:	**Weight (ton)**		**(% by weight)**
Concrete waste generated annually (ton):	High estimate:	1 200 000	
	Low estimate:	800 000	
Waste by population (based on high estimate)		0,222	
Concrete rubble (% of total Concrete-waste)			100 %
Concrete rubble generated annually (ton):	High estimate:	1 200 000	
	Low estimate:	800 000	
Concrete recycling level (% of rubble generated)			90 %
Annual production of recycled concrete aggregate (RCA)	High estimate:	1 080 000	
	Low estimate:	720 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			0 %
Unbound application below ground (as road base, backfill etc.)			100 %
Unbound application above ground (as road surface etc.)			0 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	0	
	Low estimate:	0	
Unbound application below ground (as road base, backfill etc.)	High estimate:	1 080 000	
	Low estimate:	720 000	
Unbound application above ground (as road surface etc.)	High estimate:	0	
	Low estimate:	0	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			21 %
1 - 10 mm			30 %
10 - 30 mm			44 %
> 30 mm			5 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	226 800	
	Low estimate:	151 200	
1 - 10 mm	High estimate:	324 000	
	Low estimate:	216 000	
10 - 30 mm	High estimate:	475 200	
	Low estimate:	316 800	
> 30 mm	High estimate:	54 000	
	Low estimate:	36 000	
References: Current waste data for Denmark are based on:	Affaldstatistik 2002, Miljøstyrelsen		
	Communication with Per Arevad, RGS90 (producer of crushed concrete)		

Future situation approx. by 2010	Weight (ton)		(% by weight)
C&D waste generated annually (ton):	High estimate:	1 200 000	
	Low estimate:	800 000	
Waste by population (based on high estimate)		0,222	
Concrete rubble (% of total C&D-waste)			100 %
Concrete rubble generated annually (ton):	High estimate:	1 200 000	
	Low estimate:	800 000	
Concrete recycling level (% of rubble generated)			90 %
Annual production of RCA	High estimate:	1 080 000	
	Low estimate:	720 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			0 %
Unbound application below ground (as road base, backfill etc.)			100 %
Unbound application above ground (as road surface etc.)			0 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	0	
	Low estimate:	0	
Unbound application below ground (as road base, backfill etc.)	High estimate:	1 080 000	
	Low estimate:	720 000	
Unbound application above ground (as road surface etc.)	High estimate:	0	
	Low estimate:	0	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			21 %
1 - 10 mm			30 %
10 - 30 mm			44 %
> 30 mm			5 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	226 800	
	Low estimate:	151 200	
1 - 10 mm	High estimate:	324 000	
	Low estimate:	216 000	
10 - 30 mm	High estimate:	475 200	
	Low estimate:	316 800	
> 30 mm	High estimate:	54 000	
	Low estimate:	36 000	
References: Future waste data for Denmark are based on:	Affaldsstrategi 2005-2008, Miljøstyrelsen		
	It is speculated that more concrete in the future will be classified as dangerous waste		
	thus the recycling level may drop slightly.		

6.3 Construction and demolition waste data in Sweden

C&D-waste data for Sweden:			
Population:		9 000 000	
Survey completed by:		Åsa Nilsson (Cementa)	
Date:		08.05.2005	
Current situation:	**Weight (ton)**		**(% by weight)**
C&D waste generated annually (ton):	High estimate:	2 000 000	
	Low estimate:	1 800 000	
Waste by population (based on high estimate)		0,222	
Concrete rubble (% of total C&D-waste)			60 %
Concrete rubble generated annually (ton):	High estimate:	1 200 000	
	Low estimate:	1 080 000	
Concrete recycling level (% of rubble generated)			60 %
Annual production of recycled concrete aggregate (RCA)	High estimate:	720 000	
	Low estimate:	648 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			3 %
Unbound application below ground (as road base, backfill etc.)			92 %
Unbound application above ground (as road surface etc.)			5 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	21 600	
	Low estimate:	19 440	
Unbound application below ground (as road base, backfill etc.)	High estimate:	662 400	
	Low estimate:	596 160	
Unbound application above ground (as road surface etc.)	High estimate:	36 000	
	Low estimate:	32 400	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			10 %
1 - 10 mm			25 %
10 - 30 mm			40 %
> 30 mm			25 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	72 000	
	Low estimate:	64 800	
1 - 10 mm	High estimate:	180 000	
	Low estimate:	162 000	
10 - 30 mm	High estimate:	288 000	
	Low estimate:	259 200	
> 30 mm	High estimate:	180 000	
	Low estimate:	162 000	
References: Current waste data for Sweden are based on:	Concrete recycling report 2002, confidential report within Heidelberg Cement		
	personal experience and discussions		
	Very little data available,		

Future situation approx. by 2010	Weight (tonn)		(% by weight)
C&D waste generated annually (ton):	High estimate:	2 000 000	
	Low estimate:	1 800 000	
Waste by population (based on high estimate)		0,222	
Concrete rubble (% of total C&D-waste)			60 %
Concrete rubble generated annually (ton):	High estimate:	1 200 000	
	Low estimate:	1 080 000	
Concrete recycling level (% of rubble generated)			70 %
Annual production of RCA	High estimate:	840 000	
	Low estimate:	756 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			5 %
Unbound application below ground (as road base, backfill etc.)			90 %
Unbound application above ground (as road surface etc.)			5 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	42 000	
	Low estimate:	37 800	
Unbound application below ground (as road base, backfill etc.)	High estimate:	756 000	
	Low estimate:	680 400	
Unbound application above ground (as road surface etc.)	High estimate:	42 000	
	Low estimate:	37 800	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			10 %
1 - 10 mm			25 %
10 - 30 mm			40 %
> 30 mm			25 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	84 000	
	Low estimate:	75 600	
1 - 10 mm	High estimate:	210 000	
	Low estimate:	189 000	
10 - 30 mm	High estimate:	336 000	
	Low estimate:	302 400	
> 30 mm	High estimate:	210 000	
	Low estimate:	189 000	
References: Future waste data for Sweden are based on:	Estimations		

6.4 Construction and demolition waste data in Iceland

C&D-waste data for Iceland:			
Population:		280 000	
Survey completed by:		Gísli Guðmundsson (IBRI)	
Date:		11.06.2004	
Current situation:		**Weight (tonn)**	**(% by weight)**
C&D waste generated annually (ton):	High estimate:	1 112 049	
	Low estimate:		
Waste by population (based on high estimate)		3,972	
Concrete rubble (% of total C&D-waste)			5 %
Concrete rubble generated annually (ton):	High estimate:	52 266	
	Low estimate:	0	
Concrete recycling level (% of rubble generated)			100 %
Annual production of recycled concrete aggregate (RCA)	High estimate:	52 266	
	Low estimate:	0	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			
Unbound application below ground (as road base, backfill etc.)			
Unbound application above ground (as road surface etc.)			100 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	0	
	Low estimate:	0	
Unbound application below ground (as road base, backfill etc.)	High estimate:	0	
	Low estimate:	0	
Unbound application above ground (as road surface etc.)	High estimate:	52 266	
	Low estimate:	0	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			10 %
1 - 10 mm			
10 - 30 mm			
> 30 mm			90 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	5 227	
	Low estimate:	0	
1 - 10 mm	High estimate:	0	
	Low estimate:	0	
10 - 30 mm	High estimate:	0	
	Low estimate:	0	
> 30 mm	High estimate:	47 040	
	Low estimate:	0	
References: Current waste data for Iceland are based on:	Data from: Edda Lilja Sveinsdóttir, et al. (2002) Construction and demolition waste in Iceland.		
	Part 1: Classification and quantity. IBRI report 02-03		

6.5 Construction and demolition waste data in Finland

C&D-waste data for Finland:			
Population:		5 200 000	
Survey completed by:		Heikki Kukko (VTT)	
Date:			
Current situation:	**Weight (tonn)**		**(% by weight)**
C&D waste generated annually (ton):	High estimate:	1 600 000	
	Low estimate:	1 400 000	
Waste by population (based on high estimate)		0,308	
Concrete rubble (% of total C&D-waste)			45 %
Concrete rubble generated annually (ton):	High estimate:	720 000	
	Low estimate:	630 000	
Concrete recycling level (% of rubble generated)			50 %
Annual production of recycled concrete aggregate (RCA)	High estimate:	360 000	
	Low estimate:	315 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			10 %
Unbound application below ground (as road base, backfill etc.)			87 %
Unbound application above ground (as road surface etc.)			3 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	36 000	
	Low estimate:	31 500	
Unbound application below ground (as road base, backfill etc.)	High estimate:	313 200	
	Low estimate:	274 050	
Unbound application above ground (as road surface etc.)	High estimate:	10 800	
	Low estimate:	9 450	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			10 %
1 - 10 mm			24 %
10 - 30 mm			40 %
> 30 mm			26 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	36 000	
	Low estimate:	31 500	
1 - 10 mm	High estimate:	86 400	
	Low estimate:	75 600	
10 - 30 mm	High estimate:	144 000	
	Low estimate:	126 000	
> 30 mm	High estimate:	93 600	
	Low estimate:	81 900	
References: Current waste data for Finland are based on:	1)Perälä & Nippala:Construction wastes ande their utilization VTT research notes.1936.		
	Espoo 1998. 67 p,+ app. 20 p. in Finnish (corrected on the basis of construction volume)		
	2) Recycling of concrete and concrete slurry in the concrete industry		
	Confederation of Finnish Construction Industries RT. 2002. 33 p. + app. 7 p.In Finnish		

Future situation approx. by 2010	Weight (tonn)		(% by weight)
C&D waste generated annually (ton):	High estimate:	1 700 000	
	Low estimate:	1 500 000	
Waste by population (based on high estimate)		0,327	
Concrete rubble (% of total C&D-waste)			60 %
Concrete rubble generated annually (ton):	High estimate:	1 020 000	
	Low estimate:	900 000	
Concrete recycling level (% of rubble generated)			70 %
Annual production of RCA	High estimate:	714 000	
	Low estimate:	630 000	
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)			20 %
Unbound application below ground (as road base, backfill etc.)			70 %
Unbound application above ground (as road surface etc.)			10 %
Estimate use of RCA (% of annual production)			
Bound applications (as aggregate for new concrete etc.)	High estimate:	142 800	
	Low estimate:	126 000	
Unbound application below ground (as road base, backfill etc.)	High estimate:	499 800	
	Low estimate:	441 000	
Unbound application above ground (as road surface etc.)	High estimate:	71 400	
	Low estimate:	63 000	
Estimated particle distribution for RCA (% of annual production)			
< 1 mm			12 %
1 - 10 mm			26 %
10 - 30 mm			40 %
> 30 mm			22 %
Estimated particle distribution (by weight of annual production):			
< 1 mm	High estimate:	85 680	
	Low estimate:	75 600	
1 - 10 mm	High estimate:	185 640	
	Low estimate:	163 800	
10 - 30 mm	High estimate:	285 600	
	Low estimate:	252 000	
> 30 mm	High estimate:	157 080	
	Low estimate:	138 600	
References: Future waste data for Finland are based on:	1)Perälä & Nippala:Construction wastes ande their utilization VTT research notes.1936.		
	Espoo 1998. 67 p,+ app. 20 p. in Finnish (corrected on the basis of construction volume)		
	2) Perälä & Vainio: Construction waste from the Helsinki metropolitan area building sites		
	Helsinki Metropolitan Area Council (YTV). Publication C2004/13. 13 p.		