



No. B2499  
February 2025

# CO<sub>2</sub> uptake in cement-containing products

Background and calculation models for implementation in national greenhouse gas emission inventories

**Commissioned by** Cembureau, Cementa AB and IVL research foundation

Håkan Stripple   Christer Ljungkrantz   Tomas Gustafsson   Ronny Andersson



**Authors:** Håkan Stripple   Christer Ljungkrantz   Tomas Gustafsson   Ronny Andersson

**Commissioned by:** Cembureau - Association Européenne du Ciment, Cements AB and IVL  
research foundation.

**Report number:** B2499

**ISBN:** 978-91-7883-660-4

**© IVL Swedish Environmental Research Institute 2025**

IVL Swedish Environmental Research Institute Ltd.,

P.O Box 210 60, S-100 31 Stockholm, Sweden

Phone +46-(0)10-788 65 00 // [www.ivl.se](http://www.ivl.se)

This report has been reviewed and approved in accordance with IVL's audited and approved management system.

# Contents

Contents.....	3
Preface .....	5
Summary .....	8
Abbreviations and definitions.....	11
1 Introduction .....	13
1.1 Background.....	13
1.2 Purpose and goal.....	14
2 Theoretic background to CO <sub>2</sub> uptake in cement-containing products .....	16
2.1 General description .....	16
2.2 Maximum uptake of CO <sub>2</sub> for non-traditional raw materials for clinker production .....	19
3 IPCC documentation of CO <sub>2</sub> emissions and uptake.....	21
4 General description of CO <sub>2</sub> uptake models for cement-containing products.....	23
5 Proposed CO <sub>2</sub> uptake models for cement-containing products .....	25
5.1 Overview description and strategies .....	25
5.2 Historical use of cement clinker affecting the present uptake .....	25
5.3 IVL Tier 3 Annual CO <sub>2</sub> uptake model - User developed models Advanced methodology I .....	30
5.3.1 Introduction and background .....	30
5.3.2 Primary concrete products .....	31
5.3.2.1 Background uptake technology for uptake in primary concrete products.....	31
5.3.2.2 Methodology for modeling .....	32
5.3.3 End-of-Life processes .....	38
5.3.3.1 Background uptake technology for uptake in end-of-life processes .....	38
5.3.3.2 Methodology for modeling .....	43
5.3.4 Secondary concrete products .....	48
5.3.4.1 Background uptake technology.....	48
5.3.4.2 Methodology for modeling .....	50
5.3.5 Future supporting software development for an IVL Tier 3 model .....	55
5.4 IVL Tier 2 model for annual CO <sub>2</sub> uptake - Advanced methodology II.....	56
5.4.1 Proposed CO <sub>2</sub> uptake model for IVL Tier 2 .....	56
5.4.1.1 Primary use stage - Advanced methodology II .....	57
5.4.1.2 End-of-life stage (demolishing, crushing and storage) .....	60
5.4.1.3 Secondary use .....	61
5.4.1.4 Cement constituents and concrete additions .....	61
5.4.2 Introduction .....	62

5.4.3	The primary use stage, results from different studies.....	62
5.4.3.1	The Advanced methodology I type used in previous studies .....	63
5.4.3.2	The Advanced methodology II type used in previous studies .....	65
5.4.4	Discussion of “good practice” for the Advanced methodology in the Use stage .....	69
5.4.5	The Advanced methodology I, based on wide historical data on cement and concrete use – an overview.....	70
5.4.6	The Advanced methodology II, based on a single or few years data on cement and concrete use – an overview .....	70
5.4.7	End-of-life stage and secondary use.....	72
5.4.7.1	End-of-life stage (demolishing, crushing and storage) .....	72
5.4.7.2	Secondary use .....	75
5.4.8	Cement with different constituents or additions added at the concrete mixer.....	76
5.5	IVL Tier 1 model for CO <sub>2</sub> uptake - Simplified methodology.....	78
5.5.1	Proposed CO <sub>2</sub> uptake model for IVL Tier 1 .....	78
5.5.1.1	IVL Tier 1 method for annual uptake in primary use, End-of-Life and secondary use stages.....	79
5.5.2	Introduction .....	81
5.5.3	The use stage of primary product.....	82
5.5.3.1	Influence of high use of mortar/render/plaster (from the global study) .....	87
5.5.4	End-of-life (EoL) stage and secondary use.....	89
5.5.4.1	End-of-life stage (demolishing, crushing and storage) .....	89
5.5.4.2	Secondary use .....	91
5.5.5	CO <sub>2</sub> uptake with non-traditional raw materials as CaO source beside limestone .....	92
6	Discussion and conclusions.....	94
	References .....	96
	Appendix 1 – Characterization of existing CO <sub>2</sub> uptake models.....	98
	Appendix 2 – Literature overview of carbonation.....	102

# Preface

This report is a novel attempt to fill in the information and methodological gap in national and international annual greenhouse gas net emission estimations for the purpose of reporting to the United Nations Framework Convention on Climate Change (UNFCCC), in relation to CO<sub>2</sub> uptake in cement-containing products. Presently, the Intergovernmental Panel on Climate Change (IPCC) does not provide any methodology for estimations of concrete carbonation as a CO<sub>2</sub> sink. However, the Working Group I of the IPCC 6<sup>th</sup> Assessment Report recognizes the importance of CO<sub>2</sub> uptake in cement net emission accounting.

A significant amount of research is available regarding carbonation (see e.g. Appendix 2). Some CO<sub>2</sub> uptake models have been developed in different countries and a European standard [16] is available, with an annex on calculation of CO<sub>2</sub> uptake in concrete products. However, uptake methods and models adapted to the IPCC applications are missing. This is thus the origin and background of the present study. As calculation models for CO<sub>2</sub> uptake in concrete are complex, an international research team has been created to capture present research and to further develop appropriate methods and calculation models for CO<sub>2</sub> uptake. The aim of this study is to improve the net emission estimates of climate gases by providing support for improved calculation methods. It can also be used as a guideline for the national greenhouse gas calculations and as a complement to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The present report is the result of this research group's work and is intended to be used as a basis for further development work in the climate field.

The present study has been carried out by IVL Swedish Environmental Research Institute as a co-financed research project. The project is co-financed by IVL research foundation (50 %) and Cementa AB (50 %). IVL's part is part of an international project to develop methods for CO<sub>2</sub> uptake in concrete which has contributed to important scientific information. The results from this study will be made available to the IPCC and other organizations in order to include CO<sub>2</sub> uptake in concrete as a part of the global CO<sub>2</sub> net emission calculations.

## Preface to second edition

After the first edition of the report dated October 2018, the project has continued. In the subsequent project, the calculation methods have been further developed and calculation models for CO<sub>2</sub> uptake in concrete have been developed for both IVL Tier 1 and IVL Tier 2. These models are intended to be used in uptake calculations of CO<sub>2</sub> in concrete on a national basis for e.g. the national emissions reporting and for international reporting to the UNFCCC. The models can also, to some extent, be used for uptake calculations in specific concrete structures or groups of such structures. To communicate the knowledge about carbonation and its calculation methods, a web page has also been developed on IVL's website where information is presented and where calculation models and other information can be downloaded. The web page can be accessed at the following web address:

[www.ivl.se/co2-uptake-concrete](http://www.ivl.se/co2-uptake-concrete)

In connection with this continued work, it has also been found appropriate to update the existing research report that is linked to the project, where the latest information is now available. The idea is to keep both the research report and the web pages current through updating and development.

### Preface to third edition

In the previous editions, the methods for CO<sub>2</sub> uptake in concrete was focused on development of simplified methods to calculate CO<sub>2</sub> uptake in concrete on a yearly national basis. The CO<sub>2</sub> uptake methods used for such calculations are complex so there is a need for simplified methods. However, the methods need to be sufficiently reliable to meet the CO<sub>2</sub> balance requirements. These methods were denoted IVL Tier 1 and IVL Tier 2 in relation to the IPCC terminology. An advanced IVL Tier 3 method was only described briefly and in general terms. The aim of these methods was to be introduced into the IPCC Guidelines for National Greenhouse Gas Inventories and the IPCC emission factor database for the use in the yearly national CO<sub>2</sub> emission and uptake calculation for the National Inventory Report (NIR) and for the reporting to UNFCCC.

In this process, the IVL Tier 1 method proposed in the second version of the report have been investigated and evaluated by IPCC EFDB Editorial Board. In this evaluation, some disadvantages and shortcomings in the calculation methods have emerged and been pointed out by the IPCC. These shortcomings are mainly focused on the fundamental methodology used and the uncertainty that this can lead to. The IVL Tier 1 and IVL Tier 2 methods relies on global or regionally averaged default values from a number of previous studies (literature data) for uptake in primary concrete products, which can result in significant inaccuracies when applied to specific national or local conditions. The CO<sub>2</sub> uptake calculation in the second edition was based on the present cement and concrete use rather than on the historic concrete uptake stock in each nation. Some deviations also exist due to a high use of mortar/render/plaster in specific markets. The uptake model method used for CO<sub>2</sub> uptake in end-of-life processes and in use of secondary concrete product is rudimentary and need to be updated in order to improve the CO<sub>2</sub> uptake accuracy and improve the possibility for national adaptation. A fundamental shortcoming is also the lack of an advanced Tier 3 method for more accurate calculations.

This has led to the need to update this report with improved calculation methods for IVL Tier 1 and IVL Tier 2 and to develop a method for developing an advanced IVL Tier 3. This has then been implemented in this update of the present report. Predominantly, Chapter 5 has been updated.

Since the second edition of this report, the IPCC has published the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. However, no refinement or amendment was made in relation to carbonation of concrete.

The work to update the third edition was funded by Cembureau - Association Européenne du Ciment (The European Cement Association).

### **Acknowledgement**

The authors of the study want to give special thanks to the technical and scientific persons who have contributed with valuable information and views to the project.

#### First edition

Casey, Diana, Ph.D. Senior Advisor, Energy and Climate Change, Mineral Products Association.

Fonta, Philippe, Managing Director, Cement Sustainability Initiative (CSI), World Business Council for Sustainable Development (WBCSD).

Loréa, Claude, Deputy Chief Executive, Cembureau

Maringolo, Vagner, Ph.D., Cembureau



Reiners, Jochen, European Cement Research Academy, ECRA.

Sheth, Satish, PCA Consultant President, SS Prime Consulting, LLC, The Portland Cement Association (PCA)

Tennis, Paul, Ph.D. Director, Product Standards and Technology, The Portland Cement Association (PCA)

*Second edition*

Baer, Louis, Director and Assistant Council (Environment & Energy), The Portland Cement Association (PCA).

Capon, Rachel, Ph.D. Project Co-ordinator (Environmental), Mineral Products Association (MPA).

Danielsson, Stefan Emil, LCA and Climate expert, Aalborg Portland A/S, Cementir Holding.

Leese, Richard, Ph.D., Director MPA Cement, Mineral Products Association (MPA).

Loréa, Claude, Cement Director, Global Cement and Concrete Association (GCCA).

Maringolo, Vagner, Ph.D., Cembureau.

Sand Damtoft, Jesper, Director – R&D, Quality and Technical Sale Support, Aalborg Portland A/S.

Sanjuán, Miguel Ángel, PhD, Instituto Español del Cemento y sus Aplicaciones (IECA), Spanish Institute of Cement and its Applications.

Sheth, Satish, PCA Consultant President, SS Prime Consulting, LLC, Portland Cement Association (PCA).

Tennis, Paul, Ph.D. Sr. Director, Research and Product Standard, Portland Cement Association (PCA).

*Third edition*

Rob van der Meer, Industrial Policy Director, CEMBUREAU – The European Cement Association.

Tennis, Paul, Ph.D. Sr. Director, Research and Product Standard, Portland Cement Association (PCA).

Capon, Rachel, Ph.D. Project Co-ordinator (Environmental), Mineral Products Association (MPA).

Sanjuán, Miguel Ángel, PhD, Instituto Español del Cemento y sus Aplicaciones (IECA), Spanish Institute of Cement and its Applications.

**Authors of the study**

Stripple, Håkan, IVL Swedish Environmental Research Institute, [Hakan.Stripple@IVL.se](mailto:Hakan.Stripple@IVL.se)

Ljungkrantz, Christer, Cementa AB, [christer.ljungkrantz@cementa.se](mailto:christer.ljungkrantz@cementa.se)

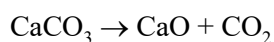
Gustafsson, Tomas, IVL Swedish Environmental Research Institute, [Tomas.Gustafsson@ivl.se](mailto:Tomas.Gustafsson@ivl.se)

Andersson, Ronny, Prof. Cementa AB, [ronny.andersson@cementa.se](mailto:ronny.andersson@cementa.se)

## Summary

The climate issue is today very important both in an international and national perspective. Many organizations and companies are actively working on climate issues and greenhouse gas emission reductions are often an important goal, as well as mapping and monitoring of greenhouse gases. At an international level, many countries report greenhouse gas emission inventories to the United Nations Framework Convention on Climate Change (UNFCCC). The international monitoring of net greenhouse gas emissions to the atmosphere is an important part of the mapping and monitoring of the global climate effects. Guidelines for national calculations of emissions and removals of greenhouse gases are presented in the framework of the Intergovernmental Panel on Climate Change (IPCC) and are provided in, for example, the document *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. In order for the calculations of the net greenhouse gas emissions to the atmosphere to be as accurate as possible, it is important that the guidelines and other documents are updated to reflect the latest science.

As part of the climate work for the cement and concrete industry, the estimates of carbon dioxide emissions have been analyzed with regard to the information provided in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. It shows that CO<sub>2</sub> emissions from cement production are calculated from both the combustion of different fuels in the cement kiln and from the discharging of CO<sub>2</sub> from the raw materials, mainly due to various incoming carbonates. The latter process is usually referred to as calcination and can be exemplified by the following chemical formula showing the thermal decomposition of limestone:



However, the calcination reactions in cement are not chemically stable but are reversible. This means that CO<sub>2</sub> in air reacts with hydrated cement phases in the concrete and carbonates are regenerated. This process is usually called carbonation, sometimes also referred to as recarbonation. In principle, the same amount of CO<sub>2</sub> driven off by calcination in the cement kiln can be taken up in the concrete by carbonation. However, the amount of CO<sub>2</sub> that will be taken up by carbonation in a reasonable timeframe depends on several factors. The availability of CO<sub>2</sub> for the concrete is crucial. The concrete must be exposed to the CO<sub>2</sub> in air to be able to carbonate. The transport of CO<sub>2</sub> molecules into the concrete is thus also an important factor as well as moisture factors. For example, if the concrete is crushed after use, the carbonation rate will increase considerably due to an increased concrete surface areas for the concrete. Carbonation is a slow process that can last for many years and can take place not only during the primary lifetime of the concrete product, but also in, for example, crushed concrete at end-of-life processes and as a secondary product (e.g. base course of a road or as landfilling material). The time aspect is thus an important issue and taking into account the entire lifecycle of concrete, the net CO<sub>2</sub> contribution to the atmosphere from calcination may thus be significantly reduced. This is why it is important to take the carbonation effect into account in net emission/uptake calculations. The current version of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, however, does not address carbonation as a carbon sink. This could lead to reduced accuracy in both national and global net emission calculations.

A very rough estimate is that the use of concrete today accounts for about 5 % to 8 % of the world's carbon dioxide emissions. About 50 % to 60 % of the CO<sub>2</sub> emissions from cement production emanate from the raw materials (calcination) and thus has a potential to be reabsorbed by carbonation of the



concrete, partly during the use phase of the concrete products, and partly in the end-of-life processes and in the secondary use stage. This study proposes methods and models for calculating CO<sub>2</sub> carbonation in various cement-containing products, including also mortar, render, plaster and cement/concrete additions such as ground granulated blast furnace slag (GGBS), fly ash, and lime filler.

A significant amount of research is available regarding carbonation (see e.g. Appendix 2). Some CO<sub>2</sub> uptake models have been developed in different countries and a European standard [16] is available, with an annex on calculation of CO<sub>2</sub> uptake in concrete products. However, uptake models adapted to the IPCC applications are missing. This is thus the origin and background of the present study. As calculation models for CO<sub>2</sub> uptake in concrete are complex, an international research team has been created to capture present research and to further develop appropriate methods and calculation models for CO<sub>2</sub> uptake with the aim of improving net emission estimates of climate gases and providing a basis for improved calculation methods in relation to the IPCC framework, especially the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

Accurate model calculations of national CO<sub>2</sub> uptake in concrete involve many different factors that control the uptake and thus requires advanced methods and extended data collection. Within the IPCC framework, different levels of method complexity is referred to as Tier 1 - 3, with Tier 1 being the most simplified method. A Tier 1 calculation should be applicable to national emission inventory teams, regardless of resources, and can serve as a good starting point for estimation of a new source or sink. For sources or sinks of key significance, IPCC Tier 2 or Tier 3 methods is generally preferred to achieve accurate and reliable results.

To support inclusion of uptake of CO<sub>2</sub> in concrete in national emission and sink inventories, it is essential that methods of different complexity is developed. In this study, calculations methods corresponding to IPCC Tier 1, Tier 2 and Tier 3 are presented. The calculation methods in this study are based on previous research in the area. The IVL Tier 1 estimate is a simplified calculation method that can be used by almost all national calculation groups with a minimum of input data. The proposed IVL Tier 1 CO<sub>2</sub> uptake average value is basically estimated today to 0.23 (23 %) of the calcination emissions from the process. This includes the CO<sub>2</sub> uptake in existing concrete structures, in end-of-life processes, and at secondary use. The IVL Tier 2 method is a more complex calculation method that can be used in the national calculation groups but still with some simplifications. The Tier 3 method opens up for the use of complex computer models for the uptake calculations that requires more knowledge and input data. Such models have been developed in a few countries on a research basis. In the IVL Tier 3 in this report, Chapter 5.3, the proposed methodology is presented in detail.

In this study, the methodological foundation for accurate estimations of uptake in concrete is presented in an IVL Tier 3 method that would require advanced modelling and vast knowledge on national concrete circumstances, which may be both resource and time consuming. Thus, in order for such calculations to be implemented in many countries with high quality, while being cost effective, common global computer models should be developed. These models can then be used for national calculations after a local adaptation to national inputs.

We intend this study to be used as a guideline for the emission inventory staff involved in national greenhouse gas calculations but also for other relevant stakeholders. Greenhouse gas emission and removal inventories for reporting to the UNFCCC is usually under the responsibility of the Ministry or nationally appointed organizations in each reporting country. This reporting can usually be reached via the national Ministry of Environment or the national Environmental Protection Agency



Report B2499 CO<sub>2</sub> uptake in cement-containing products – Background and calculation models for implementation in national greenhouse gas emission inventories

(EPA). From a technical and calculation point of view and due to its complexity, it is recommended that the national CO<sub>2</sub> uptake calculations for concrete are performed as a cooperation between the nationally appointed emission inventory team, the national cement and concrete industry, the construction industry, and national statistics organisations.

# Abbreviations and definitions

Calcination:	Is, in this case, defined as the thermal decomposition of mainly calcium carbonate (CaCO <sub>3</sub> ) or other carbonates under the formation of CO <sub>2</sub> .
Carbonated concrete:	Part of concrete where carbonation has occurred and colorless indication with phenolphthalein solution shows that pH has been lowered to less than about 8. Additional CO <sub>2</sub> uptake may have occurred in areas where pH change has not yet taken place.
Carbonated zone:	Part of concrete that is carbonated.
Carbonation depth:	Distance from surface to where colorless indication with phenolphthalein solution shows that pH has been lowered to less than about 8. Additional uptake of CO <sub>2</sub> may have occurred beyond the carbonation front, prior to pH change.
Carbonation rate:	The carbonation rate depends on several factors such as the chemical reaction rate, mass transport of CO <sub>2</sub> , humidity, temperature, porosity, CO <sub>2</sub> concentration in ambient air etc. For practical reasons the carbonation rate is often determined by measuring the depth of carbonation as function of time. It can then be expressed as mm/ $\sqrt{\text{year}}$ .
Carbonation:	A chemical reaction by which CO <sub>2</sub> penetrates the concrete and reacts with the hydration products, forming mainly calcium carbonate. In this report, any type of process-related CO <sub>2</sub> uptake during the cement production is not included.
CEM I:	Is a pure Portland cement.
CEM II:	Portland composite cement containing at least 65 % Portland clinker.
CEM III:	Contains at least 20 % and at most 65 % Portland cement and the remaining is blast furnace slag.
Cement:	Binder in concrete, and mortar/render/plaster and made of ground clinker, gypsum and often some added constituents such as GGBS, fly ash, silica fume, or limestone.
Clinker:	Is the sintered material produced in the cement kiln when heating the raw mix to high temperature.
CO <sub>2</sub> uptake area:	Is the area in cement containing products where CO <sub>2</sub> can be absorbed through carbonation.
Concrete:	Construction material made mainly of cement, gravel, sand, water, and possibly of additions and admixtures.

Degree of carbonation:	The amount of CO <sub>2</sub> uptake by carbonation in relation to maximum CO <sub>2</sub> uptake by carbonation. The maximum uptake of CO <sub>2</sub> can often be equated with the CO <sub>2</sub> emission from calcination that is driven off from the material. (For non-traditional raw material for clinker processing, see Chapter 2.2.) Traditionally, the degree of carbonation has been defined only within the area which has been considered carbonated and this area has been defined as the area exhibiting color change with phenolphthalein test.
DOC:	Degree of carbonation.
GGBS:	Ground granulated blast furnace slag.
Gt C:	Gigatonne carbon.
IPCC:	Intergovernmental Panel on Climate Change.
Mortar:	Is here cement-based and a mixture of cement, sand, and water. It is used as bonding agent between building materials such as bricks.
Render/Stucco:	Is here cement-based and a mixture of cement, sand, and water. It is used for outdoors rendering/stucco of surfaces. The term stucco is more common in the USA.
Plaster:	Is here cement-based and a mixture of cement, sand, and water. It is used for indoors plastering of surfaces.
MR:	Render/stucco or plaster used for surfaces.
NIR:	National Inventory Report
Portland cement:	Is a common type of hydraulic cement made of mainly ground cement clinker and a few percent gypsum.
tonne:	metric tonne = 1000 kg
UNFCCC:	United Nations Framework Convention on Climate Change.
z factor:	z-score percentile for normal distribution.

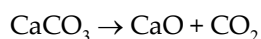
# 1 Introduction

## 1.1 Background

Concrete is the single most important building material in society and is used for a variety of products, such as houses, bridges, tunnels, roads, roof tiles, and other major and minor construction products, etc. These products constitute the primary use of concrete. After the lifetime of these products, the concrete is normally crushed and used as secondary products e.g. in roads or base course, or as fill material. The binder in concrete consists of cement. The most common cement type, Portland cement, is made by mixing limestone with other materials such as iron, aluminum and silicon containing minerals, often in the form of clay. It is also expected that the use of pre-calcined<sup>1</sup> calcium oxide sources for clinker production, beside limestone, will increase, see further Chapter 2.2. The materials are ground, mixed and burned at high temperature (1400-1450°C) in a rotary kiln to form cement clinker. In this process, the materials sinter to form clinker. Other materials may also be present in cement manufacture such as blast furnace slag and fly ash. These materials are examples of the use of recycled materials in the manufacture.

The production of clinker requires high temperature and is therefore energy intensive. The fuels used globally are mainly coal, oil and pet coke (from oil refining), but also fuels made from residues such as waste oil, solvents, plastic and scrap tires are used. The residual products can, in this way, be treated safely and efficiently in high temperature, long residence time, and with extensive cleaning of the exhaust gases while the energy content can be used. The combusted residues can, in this way, replace and reduce the use of fossil fuels. The fossil fuels used in the cement kiln give rise to CO<sub>2</sub> emissions. Emissions of other greenhouse gases such as methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are formed only in small amounts since the combustion temperature is high and the combustion condition is well-controlled in the cement kilns.

In the production of cement, most of the carbon dioxide is formed partly from the combustion of the fuels needed in clinker production (cement kiln) and partly from the calcination of the limestone, e.g. according to the reaction below:



In principle, the same amount of CO<sub>2</sub> driven off by calcination in the cement kiln can be taken up in the concrete by carbonation. However, the amount of CO<sub>2</sub> that will be taken up by carbonation in a reasonable timeframe depends on several factors. The availability of CO<sub>2</sub> for the concrete is crucial. The concrete must be exposed to the CO<sub>2</sub> in air to be able to carbonate. The transport of CO<sub>2</sub> molecules into the concrete is thus also an important factor as well as moisture factors. For example, if the concrete is crushed after use, the carbonation rate will increase considerably due to increased concrete surface areas. Carbonation is a slow process that can last for many years and can take place not only during the primary lifetime of the concrete product, but also in, for example, crushed concrete as a secondary product (e.g. base course of a road or as landfilling material). The time aspect

---

<sup>1</sup> Externally calcined material i.e. CO<sub>2</sub> are released in another process separated from and prior to the cement/concrete production.

is thus an important issue and taking into account the entire lifecycle of concrete, the net CO<sub>2</sub> contribution to the atmosphere from calcination may thus be significantly reduced.

These calcination reactions are not permanent but reversible. This means that CO<sub>2</sub> is absorbed into the concrete by a process referred to as carbonation. In principle, the same amount of CO<sub>2</sub> driven off in the cement kiln can be taken up in the concrete by carbonation. However, the amount of CO<sub>2</sub> that will be taken up by carbonation in a reasonable timeframe depends on several factors. The availability of CO<sub>2</sub> for the concrete is crucial. The concrete must be exposed to the CO<sub>2</sub> in air to be able to carbonate. The transport of CO<sub>2</sub> molecules into the concrete is thus also an important factor as well as moisture factors. For example, if the concrete is crushed after use, the carbonation rate will increase considerably due to increased concrete surface areas. Carbonation is generally a slow process that can last for many years and can take place not only during the primary lifetime of the concrete product, but also in, for example, EoL and in crushed concrete as a secondary product (e.g. base course of a road or as landfilling material). The carbonation rate can however vary significantly due to e.g. type of concrete and particle size in crushed concrete. The time aspect is thus an important issue and taking into account the entire lifecycle of concrete, the net CO<sub>2</sub> contribution to the atmosphere from calcination may thus be significantly reduced.

Today, emissions of greenhouse gases from different countries are reported, which in turn are used to support different climate strategies. Reporting takes place nationally to national authorities and internationally to the United Nations Framework Convention on Climate Change (UNFCCC). Guidelines for the emission calculation are developed and kept updated by the Intergovernmental Panel on Climate Change (IPCC). The current version, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*<sup>2</sup>, covers greenhouse gas emissions from cement and concrete processes. Both CO<sub>2</sub> emissions from fossil fuel combustion and emissions from the raw materials (calcination) are included. However, no consideration is given to the carbonation of concrete (although it is noted as an area for future work). This may be considered a shortcoming in these guidelines, which can lead to less accurate net greenhouse gas emission results. A very rough estimate is that the use of concrete today accounts for about 5-8 % of the world's carbon dioxide emissions from fossil fuels. About 50-60 % of the CO<sub>2</sub> emissions from cement production emanate from the raw materials and thus has a potential to be reabsorbed by carbonation of the concrete, partly during the use phase of the concrete products, and partly in the end-of-life and secondary use stage. In 2021, carbonation was recognized as an important carbon emission sink by Working Group I of the IPCC 6<sup>th</sup> Assessment Report [23]. We are thus convinced that carbonation is an important part of the climate calculations, and we therefore want to improve the calculations to better reflect the reality. This study proposes methods and models for calculating CO<sub>2</sub> carbonation in various cement-containing products.

## 1.2 Purpose and goal

The main purpose of the study is to provide input to the national and international greenhouse gas inventories by developing new calculation models for annual uptake of CO<sub>2</sub> in the cement and concrete sector. The goal is to include uptake of CO<sub>2</sub> by carbonation in concrete both during the lifespan of the primary concrete products and during their end-of-life and secondary use and to allocate it to the correct year. Accurate measurements and good data are always important for all

---

<sup>2</sup> In 2019, IPCC published the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. However, no refinement or amendment was made in relation to cement carbonation.

decision-making processes, and this also applies to the climate issue. The calculation methods to be used to calculate the uptake of CO<sub>2</sub> in concrete have, to some extent, been based on previously performed scientific work and models, but new methodology for uptake calculations has also been proposed in this study.

The study includes preparation of calculation methods with different complexity and accuracy (3 methods). In the IPCC's guidelines, such a level differentiation is often referred to as Tier 1, Tier 2 and Tier 3, which has also been used in this study. However, to distinguish the IPCC methods from the methods developed in this study, the methods in this study are referred to as IVL Tier 1, IVL Tier 2 and IVL Tier 3. According to the IPCC guidelines, emission/removal estimates should neither be over- nor underestimated and uncertainties reduced as far as practicable. An IPCC Tier 1 method generally is less resource demanding due to its simplification and should be possible for any country to develop, but in turn associated with the highest uncertainty. It may serve as a good starting point for making a rough estimate. More accurate results can be derived using Tier 2 or Tier 3 methods; however, more knowledge and resources are usually required. The exact definitions of the levels can vary between this study and IPCC guidelines. The method that a country will use depends on the country's ability to access statistics on cement/concrete and its use in different products.

According to the IPCC guidelines, the methods used should also depend on if a source of annual emissions or annual uptake in a carbon sink, in the country, will be defined as a "key category", either on "level" or "trend". That means that consideration should be given to categories that are of significant magnitude in later years or show a large change in magnitude over a given time series. For such key categories, IPCC guidelines states that Tier 2 or Tier 3 methods should be used. For insignificant categories (i.e. non-key categories), Tier 1 methods can be used.

The uptake of CO<sub>2</sub> in concrete, both in primary products and in end-of-life & secondary product use, is relatively slow processes that also depend on the exposure of CO<sub>2</sub> from the air. The CO<sub>2</sub> content in air today is about 425 ppm and increases by about 1-3 ppm per year. However, almost all existing concrete takes up CO<sub>2</sub> continuously with a different annual rate depending on time of completion, while annual CO<sub>2</sub> emissions from cement production is strongly linked to production volumes. The annual net contribution of CO<sub>2</sub> emissions from cement as a product in a country thus depends on both cement production and historic use of concrete. The different calculation methods relate to total CO<sub>2</sub> uptake over time but since they are time-generic they can also be used to develop different time series and annual uptake.

Since CO<sub>2</sub> uptake in cement-containing products is a measurable percentage of global CO<sub>2</sub> emissions, this represents a significant impact. In addition, the issue concerns several major industrial sectors. It mainly concerns the cement and concrete sector, but the construction sector and infrastructure construction sector can also be affected. For each industry sector, it is of course of great importance that data from the sector is accurate and that the sector's activities can be judged properly.

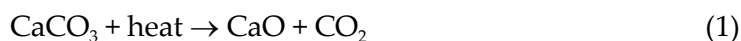
Publishing this knowledge also give new insight in how to further increase the annual CO<sub>2</sub> uptake.

## 2 Theoretic background to CO<sub>2</sub> uptake in cement-containing products

### 2.1 General description

The chemistry of cement and concrete include many different chemical reactions to achieve the specific properties of the concrete products. Different raw materials and additives are also used that can influence the chemical reactions. The focus in this study is the climate performance and behavior of different concrete products and especially the calculation of its carbon dioxide (CO<sub>2</sub>) balance. In this chapter, we will thus present the fundamental chemical reactions of CO<sub>2</sub> and its corresponding flows. A more detailed description of the processes can be found in, for example reference [11].

Portland cement is made mainly of four different components: calcium, silicone, aluminum and iron. These are supplied in cement production through various raw materials such as limestone, clay, marl, silica sand, shale, etc. (the raw mix). A main raw material in cement is limestone (CaCO<sub>3</sub>). In the cement kiln, the raw materials are heated up and CO<sub>2</sub> is driven off in the calcination reaction mainly from CaCO<sub>3</sub> according to reaction (1). In the calcination reaction, lime (CaO) and CO<sub>2</sub> are formed. CO<sub>2</sub> is released to the atmosphere in the exhaust gases from the cement kiln. CaO reacts further to form an integral part of the cement mainly as various calcium silicates, calcium aluminates, and calcium ferrites. Only a small part occurs as free CaO.



In the manufacture of concrete, water is added to the cement to form the cement paste (hydration process). The added water will then react with different substances in the cement such as tricalcium silicates and dicalcium silicates to form hydration products such as calcium silicate hydrate (C-S-H) and also calcium hydroxide (Ca(OH)<sub>2</sub>). A comprehensive presentation of cement reactions can be found in for instance [18]. The carbonation reaction is often written, for simplicity, with Ca(OH)<sub>2</sub> but CO<sub>2</sub> will also react with other components, such as the C-S-H.

Thus, both C-S-H gel and Ca(OH)<sub>2</sub> form a part of the cured concrete. CO<sub>2</sub>, mainly in the atmosphere, in contact with concrete, will primarily react with Ca(OH)<sub>2</sub> in the concrete according to the principle reaction (2) but will also react with the C-S-H. These reactions represent the uptake of CO<sub>2</sub> in concrete, which is called carbonation.

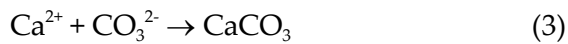


CO<sub>2</sub> is a natural part of the atmosphere. However, the concentration of CO<sub>2</sub> in the atmosphere is increasing due to an extensive global use of fossil fuels. The concentration of CO<sub>2</sub> in the atmosphere



has increased from about 280 ppm in preindustrial time to about 425 ppm today. The rate of concentration increase in the atmosphere is today about 1-3 ppm/year. An increased concentration of CO<sub>2</sub> in the atmosphere can, to some extent, also increase the rate of carbonation even if the contribution is small on a yearly basis.

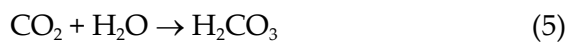
The carbonation reaction takes place in several steps. The actual uptake and sequestration reaction is the reaction between the calcium and carbonate ions (3). This reaction takes place in water phase in the pore solution in the concrete. Water and moisture are thus important parts of carbonation.



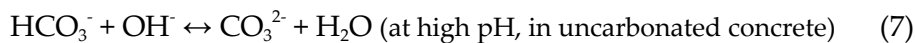
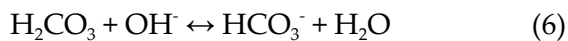
In the alkaline pore water solution in concrete, portlandite (calcium hydroxide, Ca(OH)<sub>2</sub>) can be dissolved according to reaction (4) forming calcium and hydroxide ions.



CO<sub>2</sub> is also dissolved in the alkaline pore water solution according to reaction (5) forming carbonic acid (H<sub>2</sub>CO<sub>3</sub>).



The protolysis of H<sub>2</sub>CO<sub>3</sub> in alkaline solution proceeds in two steps, (6) and (7) forming bicarbonate (HCO<sub>3</sub><sup>-</sup>) and carbonate (CO<sub>3</sub><sup>2-</sup>) ions.



In this way, Ca<sup>2+</sup> and CO<sub>3</sub><sup>2-</sup> are formed and can react and precipitate as limestone (CaCO<sub>3</sub>) in the concrete.

An important aspect is the carbonation rate. How fast can the carbonation proceed, and which are the rate determining processes? When estimating the CO<sub>2</sub> uptake in the carbonated concrete one must also consider the degree of carbonation.

The *carbonation rate* depends on several factors such as the chemical reaction rate, mass transport of CO<sub>2</sub>, humidity, temperature, porosity, CO<sub>2</sub> concentration in ambient air etc. The rate determining step could be crucial to the overall uptake rate. For practical reasons, the carbonation rate is often determined by measuring the depth of carbonation as a function of time. The depth is proportional to the square root of time. The carbonation rate can then be expressed as a constant in mm/√year.

The *degree of carbonation (DOC)* is defined as the amount of CO<sub>2</sub> taken up by carbonation in relation to the maximum CO<sub>2</sub> uptake in the carbonated volume of the concrete. The maximum uptake of CO<sub>2</sub> can often be equated with the CO<sub>2</sub> emission from calcination that is driven off from the material. This equality holds for the traditional clinker manufacturing process having calcium carbonate (CaCO<sub>3</sub>, the main mineral in limestone) as the main calcium oxide source. The evaluation of the maximum uptake of CO<sub>2</sub> for non-traditional raw materials and manufacturing processes is discussed

in Chapter 2.2. Traditionally, the degree of carbonation has been defined only within the area which has been considered carbonated and this area has been defined as the area exhibiting color change with a phenolphthalein test. (This test reveals where the depth within a cross section of concrete at which the pH has been reduced by carbonation to below about 9.) However, when calculating CO<sub>2</sub> uptake in concrete or other cement-containing products, there may be a need for a more general definition of degree of carbonation that includes all CO<sub>2</sub> reacted within the concrete (including that beyond the pH change region) in relation to all concrete.

In general, one can say that the chemical reactions presented above are relatively fast and cannot be considered as the rate determining step. However, there are several other factors that can slow down the carbonation rate. A common aspect for those factors is the access to, and transport of, molecules through the concrete. As carbonation proceeds, more and more CaCO<sub>3</sub> is precipitated in the concrete, which can reduce the permeability of the concrete. This will reduce the access of CO<sub>2</sub> to the interior of the concrete, slow down the dissolution of Ca(OH)<sub>2</sub> and thus decrease the carbonation rate.

As has been mentioned, water is required for carbonation to take place. Concrete is a porous material that allows both CO<sub>2</sub> in air and water to penetrate into the concrete. The CO<sub>2</sub> gas in the pores will dissolve in the water in the pores and carbonation can start. However, if the pores are completely filled with water, the HCO<sub>3</sub><sup>-</sup> or CO<sub>3</sub><sup>2-</sup> ions have to diffuse in the water phase into the concrete. This is a much slower process and will thus slow down the carbonation rate. Obviously, there is an optimal moisture content in concrete for a maximum carbonation rate. The optimal moisture content in concrete for carbonation has been estimated to be about 60-80 % relative humidity in the concrete.

Mainly due to the formation of CaCO<sub>3</sub> in the concrete, the carbonation rate will slow down with time. Empirical experiments have shown that the carbonation rate is proportional to the square-root of time ( $t$ ),  $\sqrt{t}$  [11,19]. Other factors that will influence the carbonation rate are porosity of the concrete, w/c ratio, cracks in the concrete, cement type and additives, and surface treatment of the concrete products. At the end-of-life of concrete products, they are demolished and often crushed for recycling purpose. When the concrete is crushed, new surfaces are created, and most of those surfaces were previously in the interior of the concrete, with limited exposure to CO<sub>2</sub>. This can dramatically increase the carbonation rate if access to CO<sub>2</sub> in air can be maintained. These smaller concrete pieces will also increase the total amount of CO<sub>2</sub> sequestered in an entire concrete volume. To estimate the uptake of CO<sub>2</sub> in concrete, it is thus important to include both the service life of the concrete products and the secondary use of the concrete after the end-of-life phase.

In the clinker manufactured in a cement kiln, there are also other compounds formed from the raw meal content that eventually can take part in the carbonation process. This has not been addressed in this study. In addition to the calcination/carbonation of the clinker from the cement kiln, there are also materials that are mixed into the cement after the cement kiln (and also mixed into concrete in concrete production). These are often called additions and can be e.g. limestone, silica fume, fly ash and ground granulated blast furnace slag (GGBS). These additions can change the carbonation rate and the reaction products of fly ash, other pozzolans, and GGBS can also take up CO<sub>2</sub>. For a complete estimation of the CO<sub>2</sub> uptake, it is thus important to consider both the change in carbonation rate and the effect on the total CO<sub>2</sub> uptake in the concrete caused by all additions. The effect on carbonation of these compounds is less known but can be taken into account in accurate uptake calculations. In the present IVL Tier 1, IVL Tier 2 and IVL Tier 3 models, only limited effects of such uptake have been included in IVL Tier 1 and more such methods are covered in IVL Tier 2 and IVL Tier 3.

## 2.2 Maximum uptake of CO<sub>2</sub> for non-traditional raw materials for clinker production

Traditionally, calcium carbonate, CaCO<sub>3</sub>, has been used as the main calcium oxide source for clinker production. The CO<sub>2</sub> released during limestone calcination (1) can be mineralized into calcium carbonate by the carbonation reaction (2) and hence the CO<sub>2</sub> emissions from raw materials (also called process or calcination emissions) equal to the maximum uptake of CO<sub>2</sub>. With the decarbonization efforts of cement industry, it is expected that the fraction of pre-calcined calcium oxide sources for clinker production will increase. In such sources, the CO<sub>2</sub> emissions from the materials have taken place before the material arrived at the cement kiln. Such sources comprise e.g. slags where CaO is bound in a pre-calcined glass, fines from concrete recycling where CaO is bound in cement hydrates, calcium hydroxide by-products, paper sludge incineration ash etc. Such materials do not release CO<sub>2</sub> upon heating, but still provide carbonatable CaO to the clinker, cement and concrete, respectively. Similarly, carbon capture technologies prevent a part of or all CO<sub>2</sub> emissions from being released, but do not alter the properties of clinker, including its maximum CO<sub>2</sub> uptake. As the CO<sub>2</sub> uptake is linked to the calcination, CO<sub>2</sub> emissions in the Simplified methodology (see Chapter 5.5), alternative raw materials and/or carbon capture technologies would lead to underestimating the actual CO<sub>2</sub> uptake. This problem can be overcome by using the carbonation potential based on the bulk chemical composition when calculating the full potential calcination emission. Already in 1957, Steinour [22] showed that the ultimate CO<sub>2</sub> uptake of a material depends in its bulk chemistry and proposed a formula.

$$CO_2^{theor} = 0.785 \times (CaO - 0.56CaCO_3 - 0.7SO_3) + 1.091 \times (MgO - 0.479MgCO_3), \quad (8)$$

where  $CO_2^{theor}$  is the maximum theoretically achievable CO<sub>2</sub> uptake related to the clinker mass (kg CO<sub>2</sub>/kg clinker) and CaO, CaCO<sub>3</sub>, SO<sub>3</sub>, MgO and MgCO<sub>3</sub> are weigh fractions of corresponding oxides and phases. Note that also other oxides such as e.g. alkalis can bind CO<sub>2</sub>. These oxides are not included in (8) since the carbonates are soluble (alkalis) or contents are low (other).

The carbonation potential according to (8) corresponds to the calcination emissions for the traditional case based on limestone and can also be used to evaluate the maximum uptake of CO<sub>2</sub> of clinkers produced using the alternative raw materials or new technologies.

Since it is only the CO<sub>2</sub> binding potential of CaO that can be estimated with the existing methods (and not MgO), and the amounts of CaCO<sub>3</sub> and SO<sub>3</sub> are small, equation (8) can be abbreviated to the form it has used in the standard EN 16757 [16].



$$\text{CO}_2 \text{ theoretic} = (M_{\text{CO}_2}/M_{\text{CaO}}) \times \text{CaO} = 0.785 \times \text{CaO}$$

where

$M_{\text{CO}_2}$  is molar mass CO<sub>2</sub> = 44 g/mol

$M_{\text{CaO}}$  is molar mass CaO = 56 g/mol

### 3 IPCC documentation of CO<sub>2</sub> emissions and uptake

Annual national greenhouse gas emissions and removals are reported by countries to international databases such as UNFCCC through their operations "Greenhouse Gas Inventory". The UNFCCC formulates its own activities as follows:

"The ultimate objective of the Climate Change Convention (UNFCCC) is to achieve "... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Estimating the levels of greenhouse gas (GHG) emissions and removals is an important element of the efforts to achieve this objective."

These databases can then be used to help assess the development of the climate from a global perspective and to develop global and regional climate strategies. It is therefore important that the uptake of CO<sub>2</sub> by carbonation in concrete and other cement-based products is included in the international emissions reporting so that accurate data on the net contribution of CO<sub>2</sub> to the atmosphere through the use of cement and concrete are obtained.

Calculation of greenhouse gas emissions and removals for reporting to the UNFCCC is usually made by the Ministry or nationally appointed organizations in each reporting country. This organization can usually be reached via the national Ministry of Environment or the national Environmental Protection Agency (EPA). From a technical and calculation point of view and due to its complexity, it is most likely and recommended that the national CO<sub>2</sub> uptake calculations for concrete are performed as a cooperation between the nationally appointed calculation group, the national cement and concrete industry, the construction industry, and national statistics organisations. Guidelines for how calculations of the climate gases are to be made are determined by control documents developed by the IPCC, see the IPCC website: <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>

The main document that regulates emission calculations and removals is 2006 IPCC Guidelines for National Greenhouse Gas Inventories.<sup>3</sup> The guidelines consist of five volumes:

- Volume 1 General Guidance and Reporting
- Volume 2 Energy
- Volume 3 Industrial Processes and Product Use
- Volume 4 Agriculture, Forestry and Other Land Use
- Volume 5 Waste

The applicable emission calculations for cement production are divided into those relating to *energy production* and those relating to *industrial processes*. The emissions from a cement kiln can thus be divided into emissions from combustion (energy production) and emissions emanating from calcining the raw materials (processes) in the calcination process. The latter CO<sub>2</sub> emissions are classified as a process emission and regulated in Volume 3 Industrial Processes and Product Use. The CO<sub>2</sub> uptake in concrete is strongly related to the CO<sub>2</sub> emissions from the raw materials and it is thus proposed that future updates of the IPCC guidelines regulate the CO<sub>2</sub> uptake in the same

---

<sup>3</sup> IPCC has later published the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; however, no refinement or amendment was made in relation to cement carbonation.

document (Volume 3) as the process emissions. This volume of the IPCC guidelines also includes emission and uptake in product use, which is the case for CO<sub>2</sub> uptake in concrete products. Product use can here also include CO<sub>2</sub> uptake in end-of-life and secondary products i.e. for example in crushed concrete.

Volume 3 Industrial Processes and Product Use includes several industrial processes of which Chapter 2 Mineral Industry Emissions is the most appropriate for this task. CO<sub>2</sub> uptake can occur in several of these product systems, which is why it is important to prepare the methodology for additional industrial processes. The uptake chapter can also be separated from the emission chapters. A revised chapter structure of Volume 3, Chapter 2 can thus be as follows, with changes marked in bold:

## Chapter 2 Mineral Industry Emissions **and removals**

### 2.1 Introduction

### 2.2 Cement production

### 2.3 Lime production

### 2.4 Glass production

### 2.5 Other process uses of carbonates

### **2.6 CO<sub>2</sub> removals**

#### **2.6.1 CO<sub>2</sub> uptake in cement containing products**

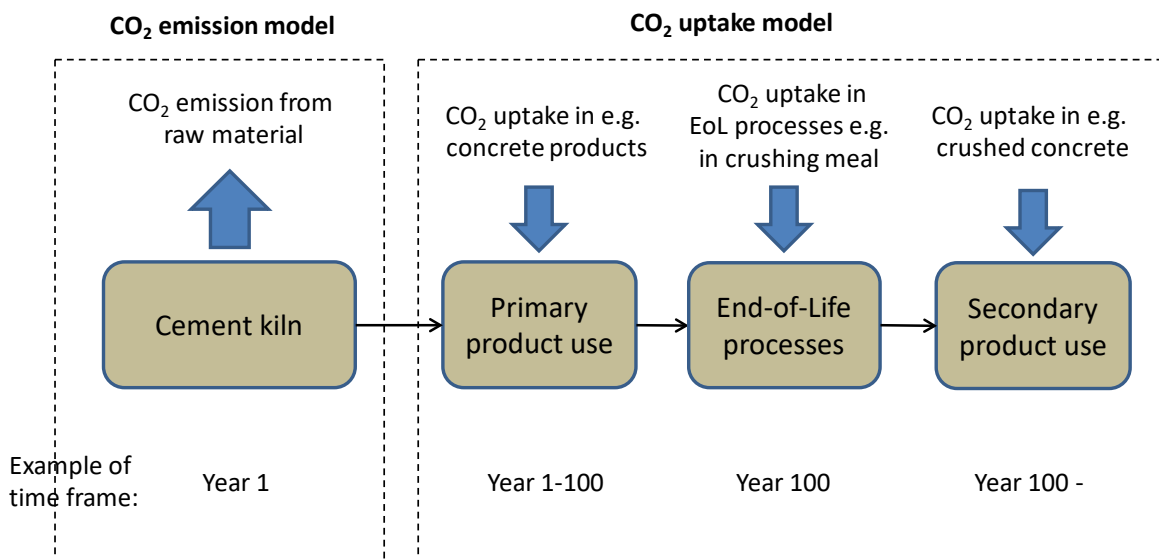
The present study can thus be an input to future revisions of the IPCC *Guidelines for National Greenhouse Gas Inventories*, but it can also serve as a calculation guideline for the nationally appointed emission calculation organizations as well as input to IPCC's emission factor database (EFDB).

# 4 General description of CO<sub>2</sub> uptake models for cement-containing products

As shown in Chapter 3, the CO<sub>2</sub> emission model for the raw materials used in a cement kiln is presented in the document *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The calculated CO<sub>2</sub> emissions are based on the amount of clinker produced by a cement kiln. This amount of CO<sub>2</sub> driven off from the material can normally be considered as the maximum theoretical uptake of CO<sub>2</sub> due to carbonation of cement containing products. In case of non-traditional raw materials, such as pre-calcined CaO sources, this will however not be the case, see Chapter 2.2.

The CO<sub>2</sub> uptake model will thus calculate the CO<sub>2</sub> uptake in different cement containing products during their service life as well as in the end-of-life processes and when used as secondary products, such as crushed concrete in a road base or as landfilling material. The emission and uptake models are illustrated in Figure 1 below.

**Figure 1 Schematic figure showing the CO<sub>2</sub> balance in cement containing products over a certain period of time.**



**Figure 1 Schematic figure showing the CO<sub>2</sub> balance in cement containing products over a certain period of time.**

The CO<sub>2</sub> uptake in concrete is a relatively slow process that takes place over many years. The first phase is uptake in e.g. concrete products or structures such as bridges, house frames, concrete tiles, concrete roads, railway sleepers, cement mortar, render etc. The carbonation process takes place from the surface of the concrete when CO<sub>2</sub> in air diffuses into the porous concrete and reacts with Ca(OH)<sub>2</sub> and other hydrated phases to form CaCO<sub>3</sub> according to the reactions described in Chapter 2. The area of concrete surfaces or the area/volume ratio of concrete products are important factors for a CO<sub>2</sub> uptake model. By knowing the total yearly use of cement clinker and how much is used in

different types of concrete categories (for example, in various strength classes, exposure types, and shapes and sizes of products and structures), the CO<sub>2</sub> uptake surface areas can be estimated. The yearly use of cement or clinker in a country can be calculated as (cement or clinker production *minus* cement or clinker exported *plus* cement or clinker imported). From the uptake surface areas, the yearly CO<sub>2</sub> uptake over the years can be calculated. For large concrete structures, only a smaller part of the concrete will be carbonated during its primary product use. Another factor that influences the CO<sub>2</sub> uptake in the concrete is the moisture content, see Chapter 2. The surface can be located in different climates, be exposed to rain or located indoors/outdoors. These factors can affect both the carbonation rate and the degree of carbonation. Also, concrete additions, such as blast furnace slag or fly ash from coal combustion, can also hydrate to produce phases that can take up CO<sub>2</sub>, which can be important to include in the calculations.

After the service life of a concrete structure, it will be demolished or wasted and eventually crushed into finer pieces for secondary use. This will increase the specific surface area and increase the carbonation rate. The total carbonation in the entire concrete volume will also be increased when the concrete is crushed into smaller pieces. However, the use of the crushed concrete must be done in such a way that air and CO<sub>2</sub> are allowed to access the increased concrete and CO<sub>2</sub> uptake surface areas. This may require some active planning of the end-of-life/secondary use processes for concrete. The knowledge about the end-of-life/secondary use processes for concrete in different countries is usually lower and the uncertainties are thus greater. The CO<sub>2</sub> uptake models for secondary use are therefore relatively uncertain. However, the CO<sub>2</sub> uptake potential is generally large for the end-of-life/secondary use phase.

In a CO<sub>2</sub> uptake model, many different levels of details can be included to improve the model performance. However, there is also a need to make simplifications in model calculations based on a few input data. A method to achieve this is to approximate the existing concrete structures in a society by applying the historical use of cement clinker for the model calculations. The maximum CO<sub>2</sub> uptake in the clinker used can be multiplied by a factor to compensate for the real uptake in both the primary use and end-of-life/secondary use phase. The IVL Tier 1-3 methods include different levels of simplifications and are further discussed in Chapter 5.



# 5 Proposed CO<sub>2</sub> uptake models for cement-containing products

## 5.1 Overview description and strategies

This chapter presents the calculation methods for the uptake of CO<sub>2</sub> in cement-containing products developed in this study. The bases for the calculation methods are also presented. Three different calculation methods and levels have been developed, which have different calculation complexity and accuracy. Generally, the more complex model, the more accurate estimated annual CO<sub>2</sub> uptake. As the uptake of CO<sub>2</sub> occurs in the standing concrete stock from year 1900 until today, common for the three models is that the calculated annual uptake preferably should be based on long historical time series on clinker use in a country. Chapter 5.2 describes how the present uptake in concrete is related to the historical use of cement clinker. The chapter also provides guidance how to develop long time series of clinker use if national data is not available.

In Chapter 5.3, the IVL Tier 3 method for an advanced modelling of annual CO<sub>2</sub> uptake is presented for primary use, end-of-life and secondary use of cement products. Uptake in primary use is modelled by concrete type and exposure conditions. Detailed data input is needed to set up the IVL Tier 3 model, but where national input is not available, standard values are provided by concrete type and exposure conditions. IVL Tier 3 End-of-life modelling takes into account factors for carbonation in EoL aggregate fractions. Uptake in secondary use of cement basically follows the same principles as for primary use and thus requires similar data input.

The less advanced method, IVL Tier 2, presented in Chapter 5.4, is based on the same methodology as the IVL Tier 3 but at a lower level of complexity. Different levels of simplifications are presented depending on available information in a country.

The aim of the IVL Tier 1 method, presented in Chapter 5.5, is to provide guidance on how to make a rather simple estimate of annual CO<sub>2</sub> uptake, without large resources being spent on data collection and other research. It is based on estimations of historical clinker use and predefined uptake factors for primary use, end-of-life and secondary use, respectively.

The different calculation methods relate to an annual uptake but since they are time-generic, they can also be used to develop different time series.

## 5.2 Historical use of cement clinker affecting the present uptake

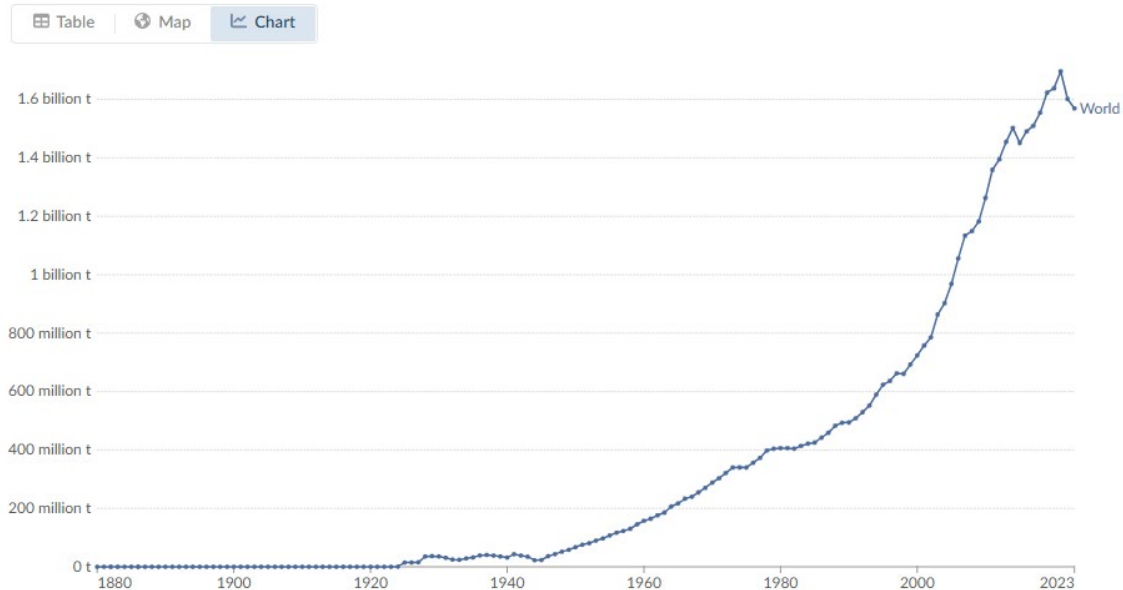
Portland cement, the most common form used today, was developed in the early 19th century by Joseph Aspdin, an English mason, who patented the process in 1824. He named it "Portland" because of its resemblance to a type of stone quarried on the Isle of Portland in Dorset, England. By 1900, the global use of cement was still relatively low compared to modern standards, but industrialization

and urbanization were driving growth. Exact figures for global cement production are hard to come by for that year but estimates suggest it was around 10 million tonnes corresponding to about 9.5 million tonnes cement clinker. Most of this cement was produced in Europe and the United States, with Portland cement quickly becoming the dominant material for modern construction. An estimation of the annual global CO<sub>2</sub> emissions from cement production over the years since 1880 is shown in Figure 2 below. These CO<sub>2</sub> emissions are very strongly related to the yearly global cement production.

## Annual CO<sub>2</sub> emissions from cement

Annual emissions of carbon dioxide (CO<sub>2</sub>) from cement, measured in tonnes.

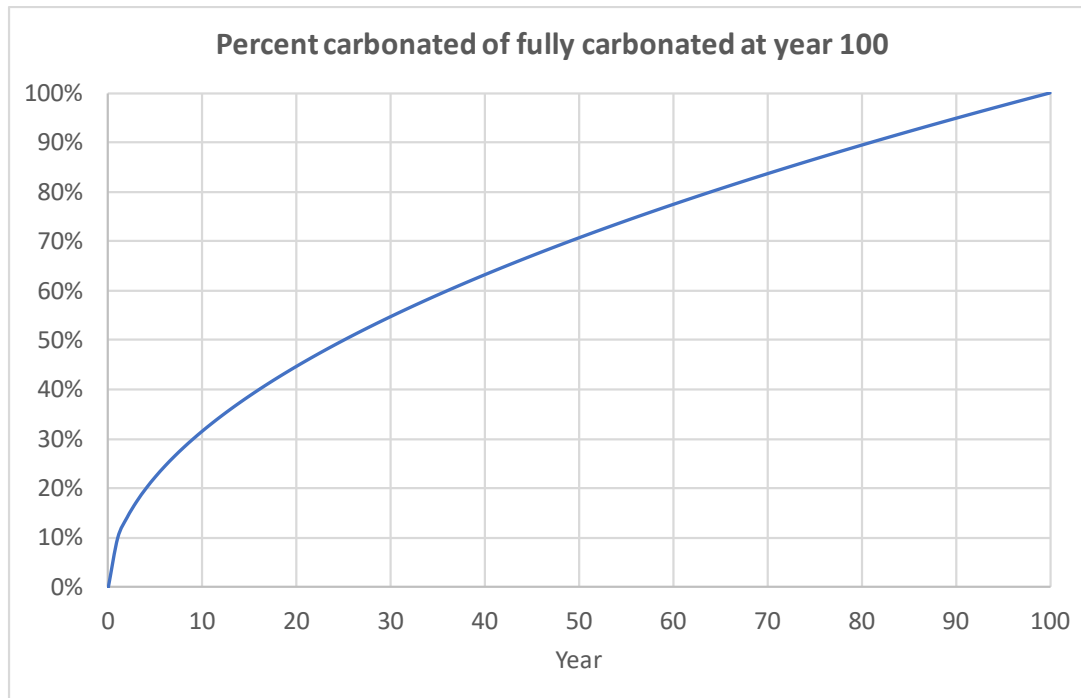
Our World  
in Data



**Figure 2 Annual CO<sub>2</sub> process emissions from cement production. The figures strongly correlate to the amount of cement produced. Data source: Global Carbon Budget (2024) – with major processing by Our World in Data**

Cement produced before 1900 is still involved in a slow uptake of CO<sub>2</sub>. This process continues for decades, even centuries, and can partially offset some of the CO<sub>2</sub> emissions produced during cement production. Portland cement from the 19th century continues to take up CO<sub>2</sub>, albeit at a slow rate. However, this uptake only accounts for a small fraction of the emissions initially produced during its manufacture and the manufacturing at that time was small. Statistical information about the production and use of cement prior to 1900 is scarce in most countries. Thus, it is proposed that CO<sub>2</sub> uptake in concrete before 1900 is neglected in the uptake methodology. This will thus contribute to a very small underestimation of the CO<sub>2</sub> uptake in recent years. For simplification, we assume that full carbonation is reached after 100 years in various concrete products mainly for IVL Tier 1 and IVL Tier 2 methodology. However, for some fast-carbonating products, such as roof tiles, mortar, render and plaster, full carbonation can be reached in a few years. Such details can be handled in an IVL Tier 3 calculation. The uptake in concrete is not linear and most rapid in the first years. The rate of carbonation can be based on the square root of time dependency, see Figure 3 for a schematic figure of the carbonation percentage of an object that is fully carbonated after 100 years as a function of carbonation time. During the first 5 years, 22 % of the 100-years uptake takes place, which is about 50 % of the 20 first years of uptake. After 20 years, thus about 45 % of the CO<sub>2</sub> uptake has taken place.

The CO<sub>2</sub> uptake calculations is thus started at around year 1900 and continues for all years until present year. Each year is calculated separately and contributes from its starting year with an CO<sub>2</sub> uptake every year until present year. All the uptake from all previous years until present are then summarized to a total uptake of CO<sub>2</sub> in all standing concrete. The base for the calculation is the use of cement clinker in a country from around 1900 until present year. The national use of cement clinker is defined as: Produced cement clinker - Export of cement clinker + Import of cement clinker.



**Figure 3 Schematic figure showing the square root effect of carbonation. The figure shows the carbonation percentage of an object that is fully carbonated after 100 years as a function of carbonation time.**

Figure 3 above presents the square root effect of carbonation with the assumption that full carbonation is reached after 100 years of cement use. This assumption is of course largely dependent of the type of cement product, where e.g. mortar/render/plaster and cement roof tiles can have a shorter service life but also a shorter time to “full” carbonation.

The basis for the IVL Tier 1-3 model calculations is the annual use of cement clinker. Statistics on annual production, import and export of cement clinker is readily available in many countries via national statistics agencies. However, historical data back to early 1900 may be less documented. The use of cement clinker was low in most countries until about the 1950's, when rapid development of concrete buildings started in several regions (see Figure 2). The historical use of cement clinker is connected to economic growth and thus has large national and regional variations. Depending on the timing for rapid increase in cement clinker use, today's uptake in cement products may vary considerably. In countries with rather stable cement use over the last 50 years, inter-annual variations in present years' carbonation are assumed to be small. On the other hand, recent rapid development of concrete structure in a society the last few decades may instead lead to an increasing trend in carbonation in recent years.

In order to use the IVL Tier 1-3 methods for calculation of annual CO<sub>2</sub> uptake in cement products, it is thus necessary to develop a time series on cement clinker use dating up to about 100 years back from the year of uptake calculation. To do this, one needs to have the basic knowledge of the historical development of cement clinker use in the country up until today. In many countries, national statistics agencies have data on cement production, import and export for the latest years. In addition, one needs to set a starting year for when significant amounts of cement clinker were used in the country and collect information on during what period(s) did rapid growth in cement as building material occur. Based on such information, approximative cement clinker use time series can be developed.

Since the square root effect of carbonation declines, it is most important to accurately know the cement clinker use in the last few years/decades (depending also on the type of concrete products used). Correspondingly, omitting carbonation in cement products from the early 1900's would likely not significantly alter the results for most countries.

To be able to calculate the uptake a specific year  $y$  (one year), the cumulative uptake during  $t$  years is subtracted by the cumulative uptake the previous ( $t-1$ ) years. Thus, the uptake during year  $y$  can be written as:

$$\text{CO}_2 \text{ uptake for a specific year } y = \text{CO}_2 \text{ cumulative uptake } (t) - \text{CO}_2 \text{ cumulative uptake } (t-1)$$

In the following Table 1, the principle of the yearly uptake calculations is shown for the primary concrete products. The rows in the table show the total uptake of CO<sub>2</sub> each year with contribution from uptake all years. The columns in the table show the CO<sub>2</sub> uptake in the concrete that was used that year ( $y$ ) and all its uptake the following years until today. So, the first column will show the uptake in the concrete that was used year 1900 and all its uptake the following years until today with adjustments for full carbonation in thin concrete constructions. The sum is thus the total CO<sub>2</sub> uptake, in concrete used in 1900, during all years. Notable is that for some products, uptake in year 2023 only rely on the cement use in the last few years. Thus, a yearly calculation of uptake in primary products need to consider different product's time to full carbonation. The calculation principles shown in Table 1 is the base for IVL Tier 3 but, to some extent, also used for IVL Tier 1 and IVL Tier 2.

**Table 1** Table showing the basic principles for the yearly calculation of CO<sub>2</sub> uptake in primary concrete products over time. These uptake principles can also be applied to end-of-life processes and secondary use.

	<b>Year of production start</b>					
<b>Year of CO<sub>2</sub> uptake</b>	<b>1900</b>	<b>1901</b>	<b>1902</b>	<b>1903</b>	<b>...y</b>	<b>Total</b>
<b>1900</b>	CO <sub>2</sub> cum. uptake 1900 (1)					$\sum$ CO <sub>2</sub> uptake 1900
<b>1901</b>	CO <sub>2</sub> cum. uptake 1900 (2) - CO <sub>2</sub> cum. uptake 1900 (1)	CO <sub>2</sub> cum. uptake 1901 (1)				$\sum$ CO <sub>2</sub> uptake 1901
<b>1902</b>	CO <sub>2</sub> cum. uptake 1900 (3) - CO <sub>2</sub> cum. uptake 1900 (2)	CO <sub>2</sub> cum. uptake 1901 (2) - CO <sub>2</sub> cum. uptake 1901 (1)	CO <sub>2</sub> cum. uptake 1902 (1)			$\sum$ CO <sub>2</sub> uptake 1902
<b>1903</b>	CO <sub>2</sub> cum. uptake 1900 (4) - CO <sub>2</sub> cum. uptake 1900 (3)	CO <sub>2</sub> cum. uptake 1901 (3) - CO <sub>2</sub> cum. uptake 1901 (2)	CO <sub>2</sub> cum. uptake 1902 (2) - CO <sub>2</sub> cum. uptake 1902 (1)	CO <sub>2</sub> cum. uptake 1903 (1)		$\sum$ CO <sub>2</sub> uptake 1903
...	...	...	...	...	...	...
<b>2023</b>	CO <sub>2</sub> cum. uptake 1900 (124) - CO <sub>2</sub> cum. uptake 1900 (123)	CO <sub>2</sub> cum. uptake 1901 (123) - CO <sub>2</sub> cum. uptake 1901 (122)	CO <sub>2</sub> cum. uptake 1902 (122) - CO <sub>2</sub> cum. uptake 1902 (121)	CO <sub>2</sub> cum. uptake 1903 (121) - CO <sub>2</sub> cum. uptake 1903 (120)	CO <sub>2</sub> cum. uptake 2023 (121) - CO <sub>2</sub> cum. uptake 2023 (120)	$\sum$ CO <sub>2</sub> uptake 2023
<b>y</b>	CO <sub>2</sub> cum. uptake 1900 (t) - CO <sub>2</sub> cum. uptake 1900 (t-1)	CO <sub>2</sub> cum. uptake 1901 (t) - CO <sub>2</sub> cum. uptake 1901 (t-1)	CO <sub>2</sub> cum. uptake 1902 (t) - CO <sub>2</sub> cum. uptake 1902 (t-1)	CO <sub>2</sub> cum. uptake 1903 (t) - CO <sub>2</sub> cum. uptake 1903 (t-1)	CO <sub>2</sub> cum. uptake y (t) - CO <sub>2</sub> cum. uptake y (t-1)	$\sum$ CO <sub>2</sub> uptake y
<b>Total</b>	$\sum$ CO <sub>2</sub> uptake 1900 concrete	$\sum$ CO <sub>2</sub> uptake 1901 concrete	$\sum$ CO <sub>2</sub> uptake 1902 concrete	$\sum$ CO <sub>2</sub> uptake 1903 concrete	$\sum$ CO <sub>2</sub> uptake y concrete	$\sum$ CO <sub>2</sub> uptake all

## 5.3 IVL Tier 3 Annual CO<sub>2</sub> uptake model - User developed models Advanced methodology I

### 5.3.1 Introduction and background

As previously stated in this report, the calculation of CO<sub>2</sub> uptake in concrete and other cement-containing products presents significant challenges. In principle, it is not possible to directly measure the uptake of CO<sub>2</sub> on-site in existing concrete products. Only the carbonation depth can be measured, and one is obliged to use calculation models to determine the CO<sub>2</sub> uptake, especially when calculating the uptake on a national level. However, by taking samples from concrete structures, the CO<sub>2</sub> uptake can be determined in laboratory. Today, there are also new sensor technologies available or under development that can measure carbonation directly in laboratory and in real applications. Examples of such sensors are pH sensors, resistivity sensors, fiber optic sensors, electrochemical sensors, CO<sub>2</sub> sensors, acoustic emission (AE) monitoring, carbonation depth sensors (optical or chemical indication) etc. Remote communication with the sensors is also possible. Most likely, these sensors will be used for sample measurements in the future.

A variety of factors also affect both the total uptake and the carbonation rate. For IVL Tier 1 and IVL Tier 2 in Chapters 5.4 and 5.5, simplified calculation methods have been developed to make approximate calculations of the CO<sub>2</sub> uptake. In order to make more accurate calculations of the CO<sub>2</sub> uptake, more advanced computer models are needed that calculate the yearly CO<sub>2</sub> uptake in the actual standing (used) concrete in each country and that take into account and include many of the different factors that affect the CO<sub>2</sub> uptake. The CO<sub>2</sub> uptake calculations also need to include the uptake in the different phases of the concrete: primary concrete products, end-of-life processes (such as crushing, sieving, temporary storage in piles etc.), and secondary concrete use including also landfills. The different parts are described more in detail in the chapters below.

The uptake of CO<sub>2</sub> takes place especially in the concrete surfaces on the existing concrete products in society and it is therefore important to have a good knowledge of these surfaces. This allows calculation models to be based on historical data for cement and concrete use in each country, supplemented by estimates of uptake surface areas and their characteristics and conditions.

Research on carbonation of concrete has been going on for a long time and some background information for complex computer models are available. As will be presented in later chapters, several countries have already developed complex computer models to make accurate calculations of CO<sub>2</sub> uptake in each country, which has been the base for the development of the IVL Tier 1 and IVL Tier 2 methods. In the IVL Tier 3 of this chapter, we want to open up the possibility for different countries to use complex national calculation models. Unlike the calculations in the IVL Tier 1 and IVL Tier 2, where the designated calculation resources in each country are expected to be able to perform the calculations independently, more complex computer models are needed to perform an IVL Tier 3 calculations, which require collaboration with various cement and concrete research organizations, construction industry, and national statistics agencies. One can also imagine that

computer models (software) for CO<sub>2</sub> uptake are developed at an international level, which can then be used in other countries following a national adaptation and with national input data. This will enable the use of advanced and more accurate models in a simplified way, which will improve the national calculation in a significant way. For validation purposes, the complex computer models can undergo a standard scientific review.

## 5.3.2 Primary concrete products

### 5.3.2.1 Background uptake technology for uptake in primary concrete products

The carbonation process starts as soon as the concrete products are built, and their concrete surfaces are exposed to CO<sub>2</sub> in the surrounding air. Of course, many different concrete products exist with different shapes, CO<sub>2</sub> exposure location and different types of concrete, which affect the CO<sub>2</sub> uptake. In Table 2, examples of primary concrete products are listed, which at least should be taken into account in an IVL Tier 3 model.

**Table 2 Example of primary concrete product groups for CO<sub>2</sub> uptake during its service life.**

<b>Primary concrete product groups - examples</b>	
House frames	Beams
Columns	Foundations
Prefab concrete houses (wall panels, precast beams, floors)	Slab on ground
Basement of houses	Concrete Masonry Units, CMUs (Blocks, cinder blocks, hollow blocks)
Concrete pipes	Concrete roads/pavements
Concrete bridges	Tunnel lining
Shotcrete	Concrete sleepers
Concrete hydropower dams	Concrete roof tiles
Concrete garden/pavement slabs	Mortar, render and plaster
Thin concrete constructions	Other concrete products

Since CO<sub>2</sub> uptake takes place from the surface of the primary concrete products, the concrete surface for the annually produced products in each country needs to be calculated. At first glance, this may appear to be a very difficult task, but can be solved with relatively good accuracy with some knowledge of the products, their percentage distribution, and the total use of cement clinker in each country. Depending on the product service life and its time to reach full carbonation, different duration of time series of annual cement clinker use is also needed.

By knowing the basic concrete recipe (especially the clinker content as kg clinker/m<sup>3</sup> concrete) for each product group and the market share of clinker (cement) to each product group, the national share of clinker (%) to each product group can be estimated. As the total use of clinker in each country is fairly known in many countries, estimations can be done of the yearly amount of clinker to each product group as well as the amount of concrete to each product group. By studying each product group, an average specific uptake surface area can be calculated as m<sup>2</sup> uptake area/m<sup>3</sup> concrete. Thus, by knowing the amount of concrete to each product group, the total national uptake area for each product is also known. By also using the amount of clinker to each product group, a weighted

average over all the product groups can be calculated for both the clinker use (kg clinker/m<sup>3</sup> concrete) and the national surface amount as m<sup>2</sup> uptake concrete/m<sup>3</sup> concrete.

### 5.3.2.2 Methodology for modeling

In the IVL Tier 3 uptake model methodology, all the uptake of CO<sub>2</sub> occurs in the standing concrete stock in the country including primary concrete use, end-of-life processes and secondary use of concrete products. This means that, in principle, all concrete that has been used in the country in the past and that still contribute with a CO<sub>2</sub> uptake need to be included in the methodology and in uptake models.

As shown in Chapter 5.2, the history of modern cement and concrete begun almost 200 years ago even if the use before year 1900 was very low. For this methodology (IVL Tier 3), it can be a good assumption to start the CO<sub>2</sub> uptake calculation year 1900. The CO<sub>2</sub> uptake calculations is thus started at year 1900 and continues for all years until present year. Each year is calculated separately and contributes from it starting year with an CO<sub>2</sub> uptake every year until present year. All the uptake from all previous year until present are then summarized to a total uptake of CO<sub>2</sub> in all standing concrete. The base for the calculation is the use of cement clinker in a country from 1900 until present year. The national use of cement clinker is defined as (produced cement clinker - export of cement clinker + import of cement clinker). For the historical clinker use, national statistical data or qualified estimations need to be used (see Chapter 5.2 for further information on how to develop historical time series on cement clinker use).

Uptake of CO<sub>2</sub> in concrete take place from the surface of the concrete. In Figure 4, the CO<sub>2</sub> uptake is presented in mathematical forms [16]. The CO<sub>2</sub> uptake occurs at surface A<sub>i</sub>. The carbonation depth in mm is direct proportional to the square root of the number of carbonation years with the constant k according to  $mm = k \cdot \sqrt{t}$ . By measuring the carbonation depth of old concrete, the constant k can be calculated for different types of concrete and exposure conditions. The constant k can be found measured and tabulated [16]. The carbonated volume can thus be calculated as (A<sub>i</sub> \* carbonation depth). It can, in many times, be difficult to reach full carbonation in the carbonated volume, so the degree of carbonation (DOC<sub>i</sub>) is often set in the range of 75-85%. The equation to calculate the cumulative CO<sub>2</sub> uptake during t years is given and explained in Figure 4. To be able to calculate the uptake a specific year y (one year), the cumulative uptake during t years is subtracted by the cumulative uptake the previous (t-1) years. Thus, the uptake during year y can be written as:

$$\text{CO}_2 \text{ uptake for a specific year } y = \text{CO}_2 \text{ cumulative uptake (t)} - \text{CO}_2 \text{ cumulative uptake (t-1)}$$

In the following Table 3, the principle of the yearly uptake calculations is shown for the primary concrete products. The rows in the table show the total uptake of CO<sub>2</sub> each year with contribution from uptake all years. The columns in the table show the CO<sub>2</sub> uptake in the concrete that was used that year (y) and all its uptake the following years until today. So, the first column will show the uptake in the concrete that was used year 1900 and all its uptake the following years until today. The sum is thus the total CO<sub>2</sub> uptake, in concrete used in 1900, during all years.

The uptake equation in Figure 4 includes several parameters that need to be calculated on a national bases to be applied for the annual national CO<sub>2</sub> uptake calculations. The correct carbonation depth factor k<sub>i</sub> needs to be used for the carbonation calculation of the different concrete products used in



the country. The  $k_i$ -factor can be found in Table 26 as well as the correction factor for  $k_i$  in Table 27 [16], which also shall be used if applicable. The correction factor is 1 if not used or needed. Also, the degree of carbonation ( $DOC_i$ ) can be found in Table 26. The use of  $k_i$  is explained in the calculation of the national values by the breakdown of the national concrete use into the different concrete products used in the country. By this methodology, the national values can be calculated more exactly by calculating each type of concrete products separately and then using the sum and weighted national average values in the national calculation model. This methodology is further described below in this chapter. Also, the carbonation area  $A_i$  as well as  $U_{icc}$  and  $C$  are calculated by this separate per-calculation method.

However, some adjustments need to be done in the calculation. Every year, there can be concrete that will be demolished and thus no longer take part in the primary concrete products carbonation. This amount of clinker/concrete must be deducted from that year's uptake calculation and transferred to the CO<sub>2</sub> uptake model methodology for CO<sub>2</sub> uptake in end-of-life processes and uptake in secondary use of concrete products, which is described below in Chapter 5.3.3 and 5.3.4.

Another modification that needs to be included is the check for full carbonation in the carbonation model. When the carbonation depth has covered the entire part of a concrete product or aggregate, it is assumed to have reached full carbonation and will not take up more CO<sub>2</sub>. The model needs to check for this limit in distance or in time to prevent the model to further uptake in these products. This is mainly important for concrete products with small dimensions like concrete roof tiles or cement products with relatively fast carbonation and thin constructions, such as mortar, render and plaster that easily can be fully carbonated. This is also important to handle in crushed hardened cement paste where small aggregates exist.

#### **Calculation methodology for national values of different concrete product groups**

To be able to calculate CO<sub>2</sub> uptake parameters on a national level, detailed specific national data are needed. These data are not easily available but need to be calculated in a national CO<sub>2</sub> uptake calculation and inventory. However, with a structured methodology, this can be achieved. This part of the chapter is a presentation of such a method for an easy calculation by breaking down the national concrete use into the use of different concrete product groups where many different basic parameters are known.

The following methodology needs to be applied for each year from approximately 1900 until present year for calculation. This needs to be performed one time. For the yearly reporting, only new calculations need to be performed for the present year of reporting.

First of all, the different concrete groups in the country, in all years from around year 1900 until today, is defined. An example of concrete groups can be found in Table 2. For each year, the amount of clinker used is known or can be estimated for each product group. In the calculation, the distribution in percent among the different concrete product groups is defined. The data then used for each product group are corresponding data for the product group i.e. one house frame can be studied or 100 different house frames to get a better statistical base. For the object(s) in the product group, the calcination emission of CO<sub>2</sub> is usually known for the clinker to each product group as approximately 0.538 kg CO<sub>2</sub>/kg clinker. Then, both the amount of clinker used, and the CO<sub>2</sub> calcination emission are known. By the concrete recipe for each group, the amount of clinker is known as kg clinker/m<sup>3</sup> concrete. For the studied object(s), both the concrete volume (m<sup>3</sup>) and the corresponding concrete uptake surface is known and thereby the useful measure of uptake area per volume concrete is known in m<sup>2</sup> surface/m<sup>3</sup> concrete. For several concrete groups like house frames

and concrete pipes, the size of the products varies significantly and therefore the measure in m<sup>2</sup> surface/m<sup>3</sup> concrete also vary why an average value need to be calculated by analyzing several representative products for the yearly production. When the different parameters for the concrete product groups are specified and calculated, a weighted average by the clinker distribution (percentage values) can be calculated e.g. for m<sup>2</sup> concrete surface/m<sup>3</sup> concrete, kg clinker/m<sup>3</sup> concrete. By knowing these annual national data and the total annual use of clinker, the total national CO<sub>2</sub> uptake area is also known. Most likely, the clinker distribution does not change drastically each year, and this exercise only need to be done for a number of years since the start of cement use.

The different products in the product groups are also exposed to different environment during use phase and are made of different concrete quality according to Table 26 and Table 27. It is therefore necessary to calculate the uptake factor  $k_i$  for all the concrete product groups as well as a national average value for  $k_i$  by calculating the weighted  $k_i$  value for all the concrete groups weighted by the annual percentage of cement clinker to the different concrete product groups. The percentage in all the concrete product groups needs to be specified for all variants of  $k_i$  in Table 26. A weighted average of each group is calculated as well as the weighted average for all the groups. In this way, an annual national value of  $k_i$  is calculated and can be used in the annual CO<sub>2</sub> uptake calculations. If additions are used in the concrete, the k-factor may need to be adjusted by a correction factor from Table 27.

**Table 3 Table showing the basic principles for the yearly calculation of CO<sub>2</sub> uptake in primary concrete products over time. These uptake principles can also be applied to end-of-life processes and secondary use.**

	<b>Year of production start</b>					
<b>Year of CO<sub>2</sub> uptake</b>	<b>1900</b>	<b>1901</b>	<b>1902</b>	<b>1903</b>	<b>...y</b>	<b>Total</b>
<b>1900</b>	CO <sub>2</sub> cum. uptake 1900 (1)					$\sum$ CO <sub>2</sub> uptake 1900
<b>1901</b>	CO <sub>2</sub> cum. uptake 1900 (2) - CO <sub>2</sub> cum. uptake 1900 (1)	CO <sub>2</sub> cum. uptake 1901 (1)				$\sum$ CO <sub>2</sub> uptake 1901
<b>1902</b>	CO <sub>2</sub> cum. uptake 1900 (3) - CO <sub>2</sub> cum. uptake 1900 (2)	CO <sub>2</sub> cum. uptake 1901 (2) - CO <sub>2</sub> cum. uptake 1901 (1)	CO <sub>2</sub> cum. uptake 1902 (1)			$\sum$ CO <sub>2</sub> uptake 1902
<b>1903</b>	CO <sub>2</sub> cum. uptake 1900 (4) - CO <sub>2</sub> cum. uptake 1900 (3)	CO <sub>2</sub> cum. uptake 1901 (3) - CO <sub>2</sub> cum. uptake 1901 (2)	CO <sub>2</sub> cum. uptake 1902 (2) - CO <sub>2</sub> cum. uptake 1902 (1)	CO <sub>2</sub> cum. uptake 1903 (1)		$\sum$ CO <sub>2</sub> uptake 1903
...	...	...	...	...	...	...
<b>2023</b>	CO <sub>2</sub> cum. uptake 1900 (124) - CO <sub>2</sub> cum. uptake 1900 (123)	CO <sub>2</sub> cum. uptake 1901 (123) - CO <sub>2</sub> cum. uptake 1901 (122)	CO <sub>2</sub> cum. uptake 1902 (122) - CO <sub>2</sub> cum. uptake 1902 (121)	CO <sub>2</sub> cum. uptake 1903 (121) - CO <sub>2</sub> cum. uptake 1903 (120)	CO <sub>2</sub> cum. uptake 2023 (121) - CO <sub>2</sub> cum. uptake 2023 (120)	$\sum$ CO <sub>2</sub> uptake 2023
<b>y</b>	CO <sub>2</sub> cum. uptake 1900 (t) - CO <sub>2</sub> cum. uptake 1900 (t-1)	CO <sub>2</sub> cum. uptake 1901 (t) - CO <sub>2</sub> cum. uptake 1901 (t-1)	CO <sub>2</sub> cum. uptake 1902 (t) - CO <sub>2</sub> cum. uptake 1902 (t-1)	CO <sub>2</sub> cum. uptake 1903 (t) - CO <sub>2</sub> cum. uptake 1903 (t-1)	CO <sub>2</sub> cum. uptake y (t) - CO <sub>2</sub> cum. uptake y (t-1)	$\sum$ CO <sub>2</sub> uptake y
<b>Total</b>	$\sum$ CO <sub>2</sub> uptake 1900 concrete	$\sum$ CO <sub>2</sub> uptake 1901 concrete	$\sum$ CO <sub>2</sub> uptake 1902 concrete	$\sum$ CO <sub>2</sub> uptake 1903 concrete	$\sum$ CO <sub>2</sub> uptake y concrete	$\sum$ CO <sub>2</sub> uptake all

## Tier 3 carbonation calculation (primary use stage)

The CO<sub>2</sub> uptake in kg for each application during t years can be calculated as:  
(The formula can be found in EN 16757, Annex BB.)

$$\text{CO}_2 \text{ cum. uptake} = (\sum(k_i \times \text{DOC}_i \times A_i)) (\sqrt{t}/1000) \times U_{\text{tcc}} \times C$$

Units: mm/year × m<sup>2</sup> × √year × kg CO<sub>2</sub>/kg clinker × kg clinker/m<sup>3</sup> concrete

Where

**CO<sub>2</sub> cum. uptake** is the total cumulative CO<sub>2</sub> uptake in kg CO<sub>2</sub> during t years.

**k<sub>i</sub>** is a constant factor for the rate of carbonation for surface i in mm/√(t).

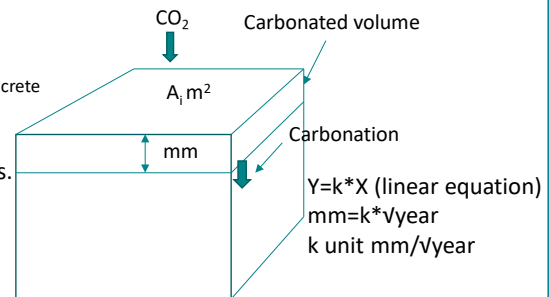
**DOC<sub>i</sub>** is the degree of carbonation for surface/volume i.

**A<sub>i</sub>** is the area of surface i in m<sup>2</sup>.

**t** is the number of years from start of carbonation.

**U<sub>tcc</sub>** is the maximum theoretical uptake in kg CO<sub>2</sub>/kg cement. The value is ≈ 0.538 for Portland cement (CEM I).

**C** is cement content in kg cement/m<sup>3</sup> of concrete.



Values of k can be found in EN 16757, Annex BB.

Values of DOC can, for example, be found in EN 16757, Annex BB.

**Figure 4 Carbonation calculation with CO<sub>2</sub> in air exposed to the concrete surface. This type of CO<sub>2</sub> uptake calculation is in principle also valid for uptake in end-of-life and in secondary use.**

Primary concrete products usually can be expected to have a service life of 50-200 years. In Table 4, Table 5 and Table 6 the carbonation depth in primary products during 50 years, 100 years and 200 years respectively are shown. In 100 years of exposure time, the carbonation depth can be in the range of 15-70 mm. This is usually less than the thickness of many primary concrete products, even if the carbonation occurs from two sides, but it indicates that a significant part of the concrete can carbonate already as primary products within 100 years. Also, a number of cement products are expected to fully carbonate with a few years, such as roof tiles, mortar, render and plaster. This is important to keep in mind for the further carbonation in end-of-life (EoL) and as secondary products. Each year, some of the primary concrete products are demolished and sent to EoL and secondary use. In the following chapters, the CO<sub>2</sub> uptake in EoL (Chapter 5.3.3) and in secondary use (Chapter 5.3.4) will be covered. In the CO<sub>2</sub> uptake model methodology, it is important to keep track of the carbonated part of the concrete at the primary use. This means that the carbonated part of the concrete as well as the non-carbonated part of the concrete need to be calculated in order to estimate the carbonation potential in EoL and secondary use so that the maximum degree of carbonation is not exceeded.

**Table 4 Carbonation depth in mm after 50 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		19.092	11.314	7.778
<b>1b</b>	Sheltered from rain		46.669	31.113	19.092
<b>1c</b>	In ground		7.778	5.657	3.536
<b>1d</b>	Under groundwater level		1.414	1.414	1.414
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	38.891	19.092	11.314	7.778
<b>2b</b>	Sheltered from rain	77.782	46.669	31.113	19.092
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	82.024	48.790	32.527	19.092
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	116.673	70.004	46.669	26.870
<b>2f</b>	In ground		7.778	5.657	3.536

**Table 5 Carbonation depth in mm after 100 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		27.000	16.000	11.000
<b>1b</b>	Sheltered from rain		66.000	44.000	27.000
<b>1c</b>	In ground		11.000	8.000	5.000
<b>1d</b>	Under groundwater level		2.000	2.000	2.000
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	55.000	27.000	16.000	11.000
<b>2b</b>	Sheltered from rain	110.000	66.000	44.000	27.000
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	116.000	69.000	46.000	27.000
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	165.000	99.000	66.000	38.000
<b>2f</b>	In ground		11.000	8.000	5.000

**Table 6 Carbonation depth in mm after 200 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		38.184	22.627	15.556
<b>1b</b>	Sheltered from rain		93.338	62.225	38.184
<b>1c</b>	In ground		15.556	11.314	7.071
<b>1d</b>	Under groundwater level		2.828	2.828	2.828
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	77.782	38.184	22.627	15.556
<b>2b</b>	Sheltered from rain	155.563	93.338	62.225	38.184
	<i>Indoors in dry climate</i>				
	*				
<b>2c</b>	With cover (Paint or wall paper)	164.049	97.581	65.054	38.184
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	233.345	140.007	93.338	53.740
<b>2f</b>	In ground		15.556	11.314	7.071

## 5.3.3 End-of-Life processes

### 5.3.3.1 Background uptake technology for uptake in end-of-life processes

The organization of the end-of-life (EoL) process for concrete in a country typically follows a structured sequence of activities aimed at minimizing environmental impact, recycling materials, and ensuring compliance with regulations. The specific practices can vary depending on national policies, infrastructure, and the level of development in waste management systems. In many countries, concrete structures are dismantled through deconstruction or selective demolition, where components like steel, wood, and concrete are separated for recycling. This approach reduces waste and increases the possibility of material recovery.

After the demolition or deconstruction phase, the concrete rubble is sorted on-site. Depending on the level of organization and infrastructure, concrete may be separated from other construction and demolition waste for more efficient recycling. Once sorted, concrete waste is transported to specialized recycling facilities. In some cases, concrete may be crushed directly on-site using mobile crushers, which reduces the need for transportation and allows reuse of materials at the demolition site itself. The concrete waste is crushed into smaller pieces, typically using industrial crushers. This is the first stage in processing, breaking down large slabs of concrete into manageable sizes. For higher quality aggregate, a secondary crushing process is often applied to further refine the size and consistency of the recycled concrete aggregate (RCA). After crushing, the material is screened to separate any remaining contaminants, such as steel rebar, which can be recycled separately. This step ensures that the recycled concrete meets specific standards for reuse.

In concrete waste recycling, different particle sizes are produced through primary crushing, secondary crushing, and sieving processes. Here is an overview of the typical particle sizes and their distribution. Please note that this is merely an example, and the particle sizes may, of course, vary. During *primary crushing*, large concrete chunks are broken down into smaller fragments suitable for further processing. The typical particle size is around *40 mm to 150 mm*. After primary crushing, the material undergoes *secondary crushing*, which reduces it further. At this stage, the concrete is broken down to produce particles between *5 mm and 40 mm*, commonly used as coarse aggregate. *Sieving* is used to separate the crushed concrete into different size fractions. Larger particles are recycled as aggregates, while finer particles *below 5 mm (fines)* are separated out for other uses like fill material or in road base construction. Fines are also used in concrete to substitute some of the aggregates. In the crushing stage, steel reinforcement bars (rebars) are also separated from the concrete for recycling. A summary is given below in Table 7 of the main fractions.

**Table 7 Main fractions from crushing and sieving of concrete in end-of-life.**

Process	Particle Size Range	Description
Primary Crushing	40 mm to 150 mm	Large chunks, reduced to manageable sizes
Secondary Crushing	5 mm to 40 mm	Further reduction, producing coarse aggregates
Sieving (Fines)	Below 5 mm	Fine particles used for other construction uses

The pieces of concrete coming from demolition to the primary crushing stage typically range in size from 300 mm to 900 mm. These chunks are often irregularly shaped and can be quite large, as they come directly from the demolition of structures like buildings, roads, or bridges. The size distribution and the percentage of each fraction vary depending on the crushing and sieving equipment, as well as the specific properties of the concrete being processed. However, general guidelines can be provided based on typical practices in concrete recycling. The following example values have been used in the study (data used in brackets).

**Coarse Aggregates:** Size is greater than 32 mm. This fraction usually represents **30-50% (40%)** of the original concrete mass. It consists of large particles of crushed concrete that can be reused as aggregate in new concrete or other construction applications.

**Medium Aggregates:** Size is 4-32 mm. This fraction typically constitutes **40-60% (50%)** of the original concrete mass. These are medium-sized particles that can be reused as aggregate for concrete production or road base material.

**Fine Aggregates:** Size is less than 4 mm. This fraction usually makes up **5-15% (10%)** of the original concrete mass. It consists of fine particles and dust, which may be used for specific applications such as filling materials or discarded, depending on local regulations and practices.

### **The dynamics and disintegration of concrete crushing**

When concrete is crushed, the fracture typically occurs in the hardened cement paste rather than in the aggregate (which is usually stone or gravel). In most cases, the fracture occurs between the cement paste and the aggregate, rather than in the aggregate itself. The cement paste, even when hardened, is usually the weaker part of the concrete compared to the aggregate. This means that when the concrete is crushed, the fracture will most often happen in or near the interfaces of the cement paste. The Interfacial Transition Zone (ITZ) is the area where the cement paste and aggregate meet, and it is often a critical zone for fractures. The ITZ is usually weaker than the rest of the

concrete because it can have microcracks, higher porosity, and lower bonding strength between the cement and the aggregate. As a result, when fractures occur, they tend to happen in or near this zone.

The aggregate (stones or gravel) in concrete is generally stronger than the cement paste. When concrete is crushed, the aggregate tends to remain intact, surrounded by fragments of cement paste. This means that the fracture surface usually leaves the aggregate relatively undamaged, while the cement-paste cracks or breaks away. Therefore, one will often see the aggregate surrounded by thinner layers of cement paste, and these layers may crack or separate from the aggregate when the concrete is further crushed. In some types of high-strength concrete, where the cement paste is very strong and well-compacted, the fracture can occur through the aggregate itself. This happens because the difference in strength between the cement paste and the aggregate is reduced, and the fracture may then occur through the weakest stones in the aggregate. However, this is less common in normal-strength concrete.

Thus, when crushing concrete, the concrete is disintegrated into usually intact aggregates surrounded by a layer of hardened cement paste and a much more crushed cement paste fraction. The total thickness of the cement paste that surrounds aggregate particles (stone or gravel) can vary significantly depending on the aggregate/cement ratio and the size of the aggregate. In a typical concrete mixture with a normal distribution of aggregate sizes, the cement paste layer around the aggregate can be anywhere between 0.5 mm and 2 mm. This is the total amount of cement paste surrounding each aggregate particle on average. It is primarily the cement paste that carbonates and take up CO<sub>2</sub>, not the aggregate. Since the aggregate is inert in this respect, the thickness of the cement paste determines the uptake of CO<sub>2</sub>. In crushed concrete, the exposed cement paste surfaces around the aggregate will carbonate more quickly, as the fracture surfaces expose fresh cement paste to atmospheric CO<sub>2</sub>.

The sizes of the crushed cement-paste fragments from crushed concrete vary significantly depending on the crushing method, the strength of the concrete, and the crushing process (e.g., primary or secondary crushing). These crushed cement-paste particles typically range from very fine particles (similar to dust) to larger chunks. The particle size distribution can range from fine dust (< 0.1 mm) to larger pieces up to several millimeters or even centimeters in size, with a considerable proportion of material typically falling into the 0.5 mm to 10 mm range. When the cement paste is crushed, especially during secondary crushing, it can produce finer particles of cement paste, often in the range of 0.01 mm to 1 mm. These smaller particles may result from the weak points in the hardened cement matrix and transition zones between the cement paste and aggregate. Larger chunks of cement paste can also be produced, often several millimeters in size. Typical sizes for these larger fragments are 5 mm to 20 mm, but in some cases, the crushed cement paste can be larger, especially after primary crushing. These larger fragments usually include not only cement paste but also small aggregates and sand, which will not carbonate.

### **Time aspects for the end-of-life (EoL) processes**

The processing and storage time for concrete during the end-of-life (EoL) phase can vary depending on the demolition practices, recycling processes, and infrastructure in place in a given region. In Table 8 below, an overview and general outline of typical timeframes for different stages in the EoL of concrete.



**Table 8 Overview and general outline of typical timeframes for different stages in the EoL of concrete (estimated average).**

Process stage	Explanations and comments	Timeframes of processes
Demolition and Dismantling	This phase can take anywhere from a few days to several weeks depending on the size and complexity of the structure being demolished. For large buildings or infrastructure projects, selective demolition or deconstruction may take longer, while simple structures can be demolished more quickly.	a few days to several weeks <b>(3 weeks)</b>
Sorting and Collection	After demolition, sorting and collecting concrete waste may take a few days to weeks. This depends on whether sorting is done on-site or off-site. Some projects may conduct initial sorting during demolition, while others transport mixed construction and demolition waste to recycling facilities for sorting.	a few days to weeks <b>(2 weeks)</b>
Crushing and Processing	The processing time for concrete can vary based on the capacity of the recycling facility and the volume of material. Typically, crushing concrete into recycled aggregate takes a few hours to several days once it reaches the facility. However, scheduling and operational delays can extend the process. The size of the recycling plant, availability of crushers, and the volume of material being processed all influence the time required.	a few hours to several days <b>(1 week)</b>
Storage Before Recycling or Reuse	Concrete rubble or crushed aggregate may be stored at a recycling facility or on a construction site for weeks to several months. The storage time depends on market demand for recycled aggregate and the availability of reuse opportunities. Some facilities have limited storage capacity, so materials may be processed and reused quickly. In other cases, where demand for recycled aggregate is lower, storage periods may be extended.	weeks to several months <b>(10 weeks)</b>
Reuse or Disposal	Once processed, recycled concrete aggregate (RCA) is either used in new construction projects or sent for final disposal, such as backfilling or landfilling. The time it takes to reuse or dispose of the material depends on the availability of construction projects and local regulations. Concrete aggregate might be stored for weeks to months until a suitable project begins. If not recycled, concrete waste could be stored at landfills indefinitely with CO <sub>2</sub> uptake possibilities.	Weeks to months or indefinitely in landfills <b>(10 weeks)</b>
<b>Total time span</b>		<b>26 weeks or 26/52 = 0.5 years</b>

**Air circulation and CO<sub>2</sub> access in stored masses of crushed concrete**

Concrete, whether intact or crushed, undergoes carbonation, in which atmospheric carbon dioxide (CO<sub>2</sub>) reacts with calcium hydroxide in the concrete to form calcium carbonate. The depth to which air (and CO<sub>2</sub>) can penetrate a pile or other formed masses of crushed concrete largely depends on the particle size and packing density of the material. Larger, loosely packed particles provide more pathways for air circulation, while fine, densely packed particles restrict airflow and slow carbonation. Thus, the configuration of the masses also affects the possibility for CO<sub>2</sub> uptake as well as moisture content as concrete must have some moisture for carbonation to occur, but excessive water can fill the pores, blocking air circulation. Key factors influencing air penetration depth and thus also carbonation can be summarised in the following aspects: pile configuration, pile compaction, moisture content, environmental conditions such as temperature and wind. Wind can promote air circulation.

Air penetration into a pile of crushed concrete is strongly influenced by its particle size distribution. Sieving the concrete into different particle sizes significantly affects how air (and CO<sub>2</sub>) moves through the pile, and thus the effectiveness of carbonation. The air void content is determined by the difference between the compacted density and the bulk density, which represents the void ratio. This is a useful measure, as dividing it by the compacted density provides a value (void content) between 0 and 100%. One way to assess this is by filling the material with water to determine the amount of voids present in the given material. This is influenced by factors such as the particle size distribution of the material. If it is a crushed product, all fractions are present simultaneously, leading to a low void content, meaning there is minimal air circulation. Conversely, by sieving out certain fractions, one can achieve a significantly higher void content, and hence greater air availability, by using only materials of e.g. size 16-32 mm. This method is known as gap-graded aggregate and is recognized and used in several applications (e.g., in unbound draining materials for railways and the aggregate in concrete roads). Thus, carbonation in crushed piles is often a balance between air circulation, uptake surface area and moisture content. This balance can be described as follows in relation to crushing and sieving.

*Large particle sizes (coarse aggregates)* give improved air circulation. When concrete is sieved into large particles (e.g., 10-50 mm), the spaces between the particles create open voids, allowing for more efficient airflow and deeper air penetration into the pile. However, that will also result in a low surface uptake area for CO<sub>2</sub>. Although air penetration is deeper, large particles offer less surface area per unit volume for carbonation reactions. Therefore, while air can circulate easily, the carbonation reaction may be slower compared to smaller particles.

*Small particle sizes (fine aggregates)* give a restricted airflow. Sieving concrete into smaller particles (e.g., less than 10 mm) results in less void space between the particles, reducing air penetration. Fine particles tend to pack more tightly, forming a denser mass with fewer channels for air to pass through. However, with a high uptake surface area. Despite restricted airflow, smaller particles have a much larger surface area exposed to CO<sub>2</sub>, which can lead to faster carbonation in the outer layers of the pile. However, deeper penetration of air and CO<sub>2</sub> into the pile is limited.

*Mixed particle sizes* can open up for an optimized air and surface area balance. A mixture of both coarse and fine particles provides a balance. The larger particles maintain air channels and circulation, while the smaller particles offer high surface area for carbonation. This can create an ideal scenario where air can reach deeper into the pile while still promoting carbonation at a significant rate. However, how this work in reality is difficult to say as smaller particles tend to clog the channels in the coarse aggregates. More research is needed in this area.

The depth of air (and CO<sub>2</sub>) penetration into a pile of crushed concrete depends on several factors and can be challenging to estimate. The following estimations have been done for the aeration of the concrete.

*Coarse Aggregates (particle size: 20-50 mm):* Large, loosely packed particles allow for greater void spaces between particles, which enhances air circulation. Estimated air penetration can be a depth of **1 to 2 meters** (or more) especially if cross strokes can be achieved. The open voids in piles composed of coarse aggregates allow air to move relatively freely through the pile. Studies of air permeability in coarse granular materials (such as gravel) suggest that air can penetrate several meters, although penetration decreases with depth as the air resistance increases and CO<sub>2</sub> reacts with the material near the surface.

*Medium Aggregates (particle size: 10-20 mm):* Medium-sized particles create more compact piles but still allow for moderate airflow. Estimated air penetration is a depth of **0.5 to 1 meter**. Medium-sized particles result in smaller voids and tighter packing, which restricts airflow compared to coarser particles. Air penetration will still occur, but the depth will be shallower because the finer particle size reduces pore space, limiting airflow beyond a certain depth.

*Fine aggregates (particle size: 0-10 mm):* Fine particles packed tightly, leaving very small voids for air to pass through. Estimated air penetration can be a depth of **10 to 30 cm**. In fine aggregates, the small particle size significantly reduces pore space, creating a dense pile where air can only penetrate the surface layers. Similar to air movement in clay soils, the tightly packed fines in concrete piles impede airflow, meaning that carbonation will be limited to the uppermost layers.

*Mixed particle sizes (Coarse and Fine Aggregate Mixture):* A pile consisting of mixed particle sizes, typically found in construction recycling, where fines fill the gaps between coarse particles. Estimated air penetration can be a depth of **0.5 to 1 meter**. A mixture of coarse and fine aggregates balances airflow and surface area for carbonation. Air can penetrate deeper than in a fine-only pile due to the presence of voids created by larger particles, but penetration is still limited by the presence of fines that fill the gaps and restrict airflow at greater depths.

The aeration of crushed concrete can in many ways be similar to aeration of soil, which is an important factor in agricultural research. The estimates above are analogous to air penetration in some soil types. For example, coarse gravel-like materials (similar to coarse aggregate) have high air permeability and can allow air to penetrate to depths of 1 to 2 meters. Fine soils like clay (similar to fine aggregate concrete) may have air penetration limited to a few centimetres or decimetres. Measurement methods used in agricultural research can probably also be useful in concrete research.

### 5.3.3.2 Methodology for modeling

At the end of its service life, concrete is often crushed and processed, either for disposal (landfill) or recycling (secondary use) purposes. During the end-of-life process, such as crushing and storage at recycling facilities, the cement paste in the concrete undergoes a chemical change known as CO<sub>2</sub> carbonation. When concrete is crushed, the exposed surface area of the cement paste increases significantly, accelerating the carbonation process. However, the presence of aggregates (stone material) in the concrete can influence how much of the cement paste can be carbonated. The hardened cement paste layer around the aggregates creates a barrier that limits CO<sub>2</sub> penetration in uncrushed concrete, but once crushed, these barriers are fragmented, allowing carbonation to occur from multiple directions in particles but also in the thin layers surrounding the aggregates.

In crushed concrete, the smaller cement-paste particles are more likely to carbonate completely because they have larger surface areas relative to their volume. Larger pieces with aggregate cores will carbonate more slowly, as the CO<sub>2</sub> needs to penetrate through the cement paste layers covering the aggregates. After crushing, particles of cement paste are no longer constrained by a single surface, and CO<sub>2</sub> can attack from multiple directions, increasing the rate and depth of carbonation. The more fragmented the concrete, the more exposed the cement paste becomes, allowing for greater carbonation potential.

Before concrete is crushed, it is common for some degree of carbonation to have already occurred during its primary use phase. This happens naturally as concrete is exposed to the atmosphere over

time. The carbonation depth in these cases depends on factors such as the concrete's porosity and quality, exposure conditions, and age. In uncrushed concrete, carbonation typically penetrates only the outer layers, with depths ranging from a few millimeters to several centimeters over decades. However, the internal cement paste within the concrete matrix remains largely uncarbonated due to limited CO<sub>2</sub> diffusion, especially in dense concrete. The proportion of pre-carbonated concrete before crushing is usually limited to the outer layers of the concrete structure. On average, only a small percentage of the total volume of concrete is carbonated during the service life of the structure. Estimates suggest that 10–30% of the concrete's surface layer will have undergone carbonation prior to the crushing process. This value depends on the dimension of the concrete product, the exposure conditions, concrete quality, and the age of the demolished structures. Once the concrete is crushed, the interior cement paste, which was not exposed to CO<sub>2</sub> during its primary use, becomes available for carbonation. Therefore, the majority of the cement paste in crushed concrete still has the potential to carbonate during storage and further processing, especially for fine particles with high surface area exposure.

To be able to estimate the CO<sub>2</sub> uptake in the end-of-life process phase, it is necessary to combine the previous information about the end-of-life process with the calculated carbonation depth for the corresponding concrete quality, exposure condition and exposure time at the end-of-life processes. The estimated process time from Table 8 indicates a possible time span of about weeks to a year. In Table 12 to Table 16, the carbonation depth is shown for a number of conditions and 1 week, 1 month, 3 months, 6 months, and 1 year. The most likely exposure No. for end-of-life processes is probably 1a and 2a Exposed to rain. It is always difficult to give an exact figure for the distribution of the concrete strength classes in the concrete waste stream, but in Table 10, an overview estimate is given. These percentages can vary based on region, local building codes, and project requirements, but this provides a general overview of the common distribution of concrete strength classes. The percentage in brackets can be used to calculate a weighted average for exposure class 1a/2a in the tables for carbonation depth. The result from that calculation is presented in Table 9. As shown from the table, the carbonation depth in end-of-life processes is most likely in the range of 1.5-2 mm with an occupation time of 0.5-1 year in the process. That carbonation depth can cover a significant amount of crushed concrete passing through the process. Do observe that this corresponds to a particle size of 3-4 mm for full carbonation. Cement paste on aggregate can thus also carbonate if they are thin. All of this requires good aeration with CO<sub>2</sub> of the material during storage.

**Table 9 Carbonation depth calculated by weighted average (Table 10) for 2a from Table 12 to Table 16.**

Exposure time at end-of-life processes	Carbonation depth weighted average for 1a and 2a (mm)
1 week	0.2885
1 month	0.6005
3 months	1.04
6 months	1.4705
1 year	2.08

**Table 10 Common percentage of use for different concrete strength class. Used estimated figure in brackets.**

Concrete Strength Class (MPa)	Common Percentage of Use	Typical Applications
< 15 MPa	5-10% (10%)	Non-structural (sidewalks, fill, light-duty)
15-20 MPa	10-20% (15%)	Residential buildings, light foundations, pavements
25-35 MPa	50-60% (60%)	General construction (residential, commercial, roads)
> 35 MPa	10-20% (15%)	High-rise buildings, bridges, industrial infrastructure

To summarize the CO<sub>2</sub> uptake in EoL, one can conclude that the uptake usually occurs within one year as this is the time frame for the waste (demolished/crushed) concrete in the EoL processes. Within this time frame, the material will move to the secondary use phase. The uptake situation can be summarized in Table 11 below. Fine aggregates can thus almost be fully carbonated within the EoL processes provided that good aeration with access to CO<sub>2</sub> can be maintained. For larger stone aggregates covered with a thin layer (1-3 mm) of cement paste, a significant carbonation can occur in EoL processes. However, for larger aggregates of cement paste, only a minor fraction will be carbonated in EoL processes. The total weighted carbonated fraction in Table 11 can thus be used as an approximation of the carbonation in EoL processes. These calculations are based on spherical aggregates with an average aggregate diameter in the mid of each size range. Carbonation from all sides of the aggregates is assumed so the carbonated volume in the aggregates is calculated as the difference between the full volume of the sphere and the non-carbonated part of the sphere, which is the volume when the diameter has been reduced by 1.5+1.5=3 mm. There can also be e.g. landfilled demolished concrete with larger concrete chunks or only primary crushed concrete with larger aggregates. In those cases, the carbonated fraction will be somewhat lower.

**Table 11 Overview of carbonation in EoL aggregate fractions.**

Phase of aggregates	Size (diameter) of aggregates	Weight fraction after crushing	Carbonation depth after 6-12 months	Carbonated fraction after EoL, 6 months
<b>Coarse Aggregates</b>	50-32 mm	40%	1.5-2 mm	20.4%
<b>Medium Aggregates</b>	4-32 mm	50%	1.5-2 mm	42.1%
<b>Fine Aggregates</b>	< 4 mm	10%	1.5-2 mm	90%
<b>Total weighted carbonated fraction</b>				<b>38.2%</b>

Below in Table 12 to Table 16, the carbonation depth are shown for different exposure times related to EoL processes, which can be 1 week, 1 month, 3 months, 6 months and 1 year. The carbonation depths are shown for different exposure conditions and different concrete qualities.

**Table 12 Carbonation depth in mm after 1 week of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		0.374	0.222	0.153
<b>1b</b>	Sheltered from rain		0.915	0.610	0.374
<b>1c</b>	In ground		0.153	0.111	0.069
<b>1d</b>	Under groundwater level		0.028	0.028	0.028
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	0.763	0.374	0.222	0.153
<b>2b</b>	Sheltered from rain	1.525	0.915	0.610	0.374
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	1.609	0.957	0.638	0.374
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	2.288	1.373	0.915	0.527
<b>2f</b>	In ground		0.153	0.111	0.069

**Table 13 Carbonation depth in mm after 1 month of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		0.779	0.462	0.318
<b>1b</b>	Sheltered from rain		1.905	1.270	0.779
<b>1c</b>	In ground		0.318	0.231	0.144
<b>1d</b>	Under groundwater level		0.058	0.058	0.058
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	1.588	0.779	0.462	0.318
<b>2b</b>	Sheltered from rain	3.175	1.905	1.270	0.779
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	3.349	1.992	1.328	0.779
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	4.763	2.858	1.905	1.097
<b>2f</b>	In ground		0.318	0.231	0.144

**Table 14 Carbonation depth in mm after 3 months of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		1.350	0.800	0.550
<b>1b</b>	Sheltered from rain		3.300	2.200	1.350
<b>1c</b>	In ground		0.550	0.400	0.250
<b>1d</b>	Under groundwater level		0.100	0.100	0.100
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	2.750	1.350	0.800	0.550
<b>2b</b>	Sheltered from rain	5.500	3.300	2.200	1.350
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	5.800	3.450	2.300	1.350
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	8.250	4.950	3.300	1.900
<b>2f</b>	In ground		0.550	0.400	0.250

**Table 15 Carbonation depth in mm after 6 months of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		1.909	1.131	0.778
<b>1b</b>	Sheltered from rain		4.667	3.111	1.909
<b>1c</b>	In ground		0.778	0.566	0.354
<b>1d</b>	Under groundwater level		0.141	0.141	0.141
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	3.889	1.909	1.131	0.778
<b>2b</b>	Sheltered from rain	7.778	4.667	3.111	1.909
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	8.202	4.879	3.253	1.909
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	11.667	7.000	4.667	2.687
<b>2f</b>	In ground		0.778	0.566	0.354

**Table 16 Carbonation depth in mm after 1 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		2.700	1.600	1.100
<b>1b</b>	Sheltered from rain		6.600	4.400	2.700
<b>1c</b>	In ground		1.100	0.800	0.500
<b>1d</b>	Under groundwater level		0.200	0.200	0.200
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	5.500	2.700	1.600	1.100
<b>2b</b>	Sheltered from rain	11.000	6.600	4.400	2.700
	<i>Indoors in dry climate</i>				
	*				
<b>2c</b>	With cover (Paint or wall paper)	11.600	6.900	4.600	2.700
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	16.500	9.900	6.600	3.800
<b>2f</b>	In ground		1.100	0.800	0.500

## 5.3.4 Secondary concrete products

### 5.3.4.1 Background uptake technology

Recycled concrete, derived from crushing and processing old concrete structures or demolition waste, is widely used in secondary applications, contributing to sustainable construction and reducing the environmental impact of concrete production. A concrete recycling plant processes this material through crushing, sieving, and sorting to create a range of products suitable for various construction and civil engineering applications. In Table 17 below, some secondary products from concrete recycling processes are shown to identify potential CO<sub>2</sub> uptake for secondary concrete products.



**Table 17 Main use of secondary concrete products.**

Secondary concrete products	Product description	Common use of the product
Recycled Concrete Aggregate (RCA)	RCA is the primary product obtained from crushing old concrete. It can be made from concrete structures like pavements, bridges, or buildings. After crushing, the material is sieved into different sizes of aggregate to suit various uses.	<p><b>Road base:</b> One of the most common applications for RCA is as a base layer in road construction, where it provides a stable foundation. Its angular texture gives it excellent load-bearing properties.</p> <p><b>Pavements and sidewalks:</b> RCA can be used as a subbase or underlay for pavements and sidewalks, providing a durable and cost-effective alternative to natural aggregates.</p> <p><b>Landscaping and drainage:</b> Coarse RCA (20-50 mm) is often used in landscaping projects, for erosion control, or as drainage material in construction.</p> <p><b>Backfill material:</b> It's frequently used to backfill trenches, retaining walls, or foundations due to its compaction properties.</p>
Recycled Fine Aggregate	Fine aggregates, or sand-like particles, are produced when concrete is crushed and sieved to smaller sizes (less than 4.75 mm). These fines are often mixed with other materials to create composite products.	<p><b>Concrete mixes:</b> Fine recycled aggregate can be used in low-strength concrete mixes, such as for footpaths, driveways, or non-structural components.</p> <p><b>Mortar, render and plaster:</b> It can be incorporated into mortar, render or plaster mixtures for less demanding applications, where strength is not the primary concern.</p> <p><b>Pavement bedding:</b> Fine aggregates are used as bedding material under paving stones, as they provide a smooth surface for levelling and compaction.</p>
Recycled Concrete Fines (Powder)	During crushing and sieving, very fine particles are produced, often referred to as "concrete fines" or "recycled concrete powder." These fines are smaller than sand and consist of cement particles, small aggregate fragments, and dust.	<p><b>Soil stabilization:</b> Concrete fines can be mixed with soils to improve load-bearing capacity and reduce permeability, particularly in road or embankment construction.</p> <p><b>Cement production (Supplementary Cementitious Material):</b> These fines may be used in the production of new cement or as a partial replacement for Portland cement, reducing the demand for virgin cement production and thus lowering carbon emissions.</p> <p><b>Landfill cover or embankment fill:</b> In some cases, concrete fines are used as a layer to cover landfills or as fill material for embankments and landscaping projects.</p> <p><b>Carbonation studies:</b> The powder-like fines provide a large surface area for CO<sub>2</sub> absorption and are often studied or used in applications related to carbon capture and sequestration.</p>
Recycled Concrete Blocks or Paving Stones	Some concrete recycling plants produce secondary concrete products by reconstituting crushed concrete. Crushed RCA and other materials can be compacted and formed into new building materials.	<p><b>Paving stones and bricks:</b> These materials are formed into new paving stones, bricks, or blocks used in landscaping, driveways, or low-traffic roadways.</p> <p><b>Precast elements:</b> In some cases, recycled concrete is used to produce precast elements like boundary walls, kerbs, or retaining walls, particularly in non-structural applications.</p>

Aggregate for Asphalt	Crushed concrete aggregate is also used as a substitute for natural aggregates in the production of asphalt. The recycled concrete replaces a portion of the virgin aggregate, while bitumen is still used as the binder.	<p><b>Road surfacing:</b> Recycled concrete aggregates are mixed with bitumen to form asphalt used in road resurfacing and other paving applications. This is common in countries with large-scale asphalt recycling programs.</p> <p><b>Driveways and parking lots:</b> Recycled concrete in asphalt mixes is also used for residential driveways and commercial parking lots.</p>
Gabion Fill Material	Gabions are wire cages filled with stones or crushed concrete used for stabilizing slopes, preventing erosion, or building retaining walls.	<p><b>Erosion control:</b> Crushed concrete is an affordable and durable option for gabion baskets, often used in riverbank stabilization, coastal defences, or hillside erosion control.</p> <p><b>Retaining walls:</b> Gabions filled with recycled concrete are also used to construct retaining walls in landscaping or civil engineering projects.</p>
Landfills		In many developed countries, about 10-20% of concrete waste still ends up in landfills. In countries with less developed recycling infrastructure, this figure can be significantly higher (e.g., up to 50% or more), sometimes as high as 80-90%.

The waste handling and use of secondary products can vary for different countries. However, in Table 18 below, an example breakdown summary estimation for the use of waste concrete is presented.

**Table 18 Example of an estimated general use of concrete waste. Used values in brackets.**

Disposal Method	Percentage	Comments	Proposed exposure type
Sent to Landfills	10-20% (10%)	Higher in regions with limited recycling infrastructure.	1c
Recycled for Road Base/Subbase	50-60% (50%)	Major application of RCA in civil and road construction.	1b
Backfill and Embankment	10-15% (10%)	Used in retaining walls, trenches, and embankments.	1c
Recycled into New Concrete Mix	5-10% (10%)	Often used in low-strength or non-structural concrete.	1b <sup>1)</sup>
Landscaping and Drainage	5-10% (10%)	Used in gardens, pathways, and drainage applications.	1c
Gabion Fill/Erosion Control	5-10% (5%)	Used in retaining walls and erosion control gabions.	1a
Soil Stabilization and Fines	5-10% (5%)	Used in soil stabilization and as supplementary cement material.	1c

<sup>1)</sup> Uptake in next product cycle.

### 5.3.4.2 Methodology for modeling

After demolition and crushing or other waste treatment, the main concrete waste stream proceeds into a secondary use phase according to Table 17 and Table 18 above. Also, for crushed concrete, the carbonation proceeds from the surface of the concrete pieces by the same principle as for primary

concrete products described in Chapter 5.3.2. However, for smaller rounded pieces, the carbonation take place from all direction, which will in principle double the size of the concrete pieces to reach full carbonation compared to carbonation from a single end. The carbonation depth in mm for different exposure times (relevant to secondary use), exposure conditions and concrete quality (concrete strength) is presented in Table 22 to Table 25, which gives an indication of the depth for full carbonation of the concrete pieces under the condition that full aeration with CO<sub>2</sub> access is present in the secondary use. To be able to calculate a general average for the carbonation depth in an average concrete mix applied in secondary use for different exposure time and exposure conditions, the data in the report have been used to calculate such an average value, which is shown in Table 19 for different exposure times at secondary use of concrete products. From the data in this table, one can conclude that, with good aeration with CO<sub>2</sub>, after 25 years of storage in secondary use, approximately all aggregates smaller than 32 mm has reached full carbonation.

**Table 19 Carbonation depth calculated by weighted average of use and exposure according to (Table 18) and concrete specification according to (Table 10) for 1a, 1b and 1c from Table 5, Table 16, Table 22, Table 23, Table 24 and Table 25.**

Exposure time at secondary use applications	Carbonation depth as weighted average for secondary use products assuming global production condition (mm)
1 year	3.1975
5 years	7.15
10 years	10.111
25 years	15.9875
100 years	31.975
500 years	71.4983

The CO<sub>2</sub> uptake methodology and modelling can thus be based on the same methodology as was used for the uptake in primary concrete product in Chapter 5.3.2. The demolished concrete that is formed each year is transferred into the CO<sub>2</sub> uptake model for end-of-life (EoL) processes and then further into the CO<sub>2</sub> uptake model for secondary use of the concrete products. For the concrete to secondary use, the same type of uptake calculation as was shown in Table 3 can now be used for the concrete to secondary use. The same type of pre-calculation as was used for the primary products can be used here as well so the different crushed fractions to secondary use can be seen as just another concrete product. However, there are some important differences. The physical shape and the composition of this concrete product is not so well defined but need to be estimated. The composition of the crushed concrete has, to some extent, been covered in Chapter 5.3.4.2.

The shape of aggregates in crushed concrete typically depends on the crushing process and the original concrete mix. Crushed concrete tends to produce irregularly shaped aggregates, often referred to as angular or sub-angular. An important parameter in all CO<sub>2</sub> uptake calculation is to define the uptake area  $A_i$  of the concrete products. An important way to calculate  $A_i$  is to estimate the concrete surface area/concrete volume ratio (m<sup>2</sup> concrete area/m<sup>3</sup> concrete,  $A/V$ ). As the concrete volume is usually known, the uptake area  $A_i$  can easily be calculated. To measure this ratio can be challenging as the surface area of the aggregates is not easy to measure. In addition to this, there is also a size distribution in a crushed concrete aggregate fraction that needs to be included in the calculations. There are advanced imaging/software methods and also methods to measure the surface area like the Brunauer-Emmett-Teller (BET) method that measure the specific surface area of the aggregates through gas adsorption techniques.

A theoretic but efficient way of calculating this ratio is by assuming a spherical or cubic form of the aggregates. In this way, the ratio of each particle size can be calculated as well as the ratio for the size distribution by calculating the weighted average of the ratio for each aggregate diameter fraction. An example of such a calculation is given below assuming spherical aggregates with a radius of r meter.

In this case:  $A_i = 4\pi r^2$   $V_i = (4/3)\pi r^3 \rightarrow A_i/V_i = 3/r$

The results from such a calculation are shown below in Table 20. With this type of calculation, an A/V ratio of 525 m<sup>2</sup> uptake area/m<sup>3</sup> of concrete can be assumed for the crushed concrete to secondary use. To put this value in perspective, the A/V ratio for spherical aggregates and different diameter has been calculated and the results are shown in Table 21 below. As shown in the table, the uptake area increases rapidly when the aggregates get smaller. However, the energy for grinding into small particles also increases dramatically. This can be calculated with Bond index and need to be taken into account when using the particle for CO<sub>2</sub> uptake. As with CO<sub>2</sub> uptake in primary concrete products and in end-of-life, it is important in the development of uptake models to keep track of the remaining potential of carbonation in the material entering secondary use and the progression of the uptake in the material so it can be stopped in the model when full carbonation is reached. It is also important to further investigate the maximum CO<sub>2</sub> uptake in relation to the calcination in the cement kiln. The Degree of Carbonation (DOC value) regulate this in the model methods. However, in very fine particles, a greater DOC value can maybe be achieved.

**Table 20 Theoretic calculation of concrete surface/volume ratio (A<sub>i</sub>/V<sub>i</sub>) for the CO<sub>2</sub> uptake calculations in crushed concrete assuming spherical aggregates.**

Phase of aggregates	Size (diameter) of aggregates	Weight fraction after crushing	Average diameter of the aggregates (mm)	Area/volume ratio, A <sub>i</sub> /V <sub>i</sub> (m <sup>2</sup> /m <sup>3</sup> )
Coarse Aggregates	50-32 mm	40%	41	146.3
Medium Aggregates	4-32 mm	50%	18	333.3
Fine Aggregates	< 4 mm	10%	2	3000
<b>Total weighted A<sub>i</sub>/V<sub>i</sub> ratio</b>				<b>525.2</b>

**Table 21 Theoretic calculation of surface Ai/volume V ratio of spherical concrete aggregates.**

Diameter of a sphere-shaped aggregate (mm)	Surface area/Concrete volume ratio (m <sup>2</sup> /m <sup>3</sup> )
0.1	60 000
1	6000
5	1200
10	600
15	400
20	300
25	240
30	200
35	171.4
40	150
45	133.3
50	120
100	60
500	12
1000	6

**Table 22 Carbonation depth in mm after 5 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
<b>No.</b>	<b>Parameters</b>	<b>Depth of carbonation in mm</b>			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		6.037	3.578	2.460
<b>1b</b>	Sheltered from rain		14.758	9.839	6.037
<b>1c</b>	In ground		2.460	1.789	1.118
<b>1d</b>	Under groundwater level		0.447	0.447	0.447
<b>2</b>	<b>Buildings</b>				
	<u>Outdoors</u>				
<b>2a</b>	Exposed to rain	12.298	6.037	3.578	2.460
<b>2b</b>	Sheltered from rain	24.597	14.758	9.839	6.037
	<u>Indoors in dry climate</u> *				
<b>2c</b>	With cover (Paint or wall paper)	25.938	15.429	10.286	6.037
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	36.895	22.137	14.758	8.497
<b>2f</b>	In ground		2.460	1.789	1.118

**Table 23 Carbonation depth in mm after 10 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		8.538	5.060	3.479
<b>1b</b>	Sheltered from rain		20.871	13.914	8.538
<b>1c</b>	In ground		3.479	2.530	1.581
<b>1d</b>	Under groundwater level		0.632	0.632	0.632
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	17.393	8.538	5.060	3.479
<b>2b</b>	Sheltered from rain	34.785	20.871	13.914	8.538
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	36.682	21.820	14.546	8.538
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	52.178	31.307	20.871	12.017
<b>2f</b>	In ground		3.479	2.530	1.581

**Table 24 Carbonation depth in mm after 25 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		13.500	8.000	5.500
<b>1b</b>	Sheltered from rain		33.000	22.000	13.500
<b>1c</b>	In ground		5.500	4.000	2.500
<b>1d</b>	Under groundwater level		1.000	1.000	1.000
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	27.500	13.500	8.000	5.500
<b>2b</b>	Sheltered from rain	55.000	33.000	22.000	13.500
	<i>Indoors in dry climate</i> *				
<b>2c</b>	With cover (Paint or wall paper)	58.000	34.500	23.000	13.500
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	82.500	49.500	33.000	19.000
<b>2f</b>	In ground		5.500	4.000	2.500

**Table 25 Carbonation depth in mm after 500 year of air exposure (with CO<sub>2</sub>) for different concrete types and exposure conditions.**

	Concrete strength	≤ 15 MPa	15-20 MPa	25-35 MPa	≥ 35 MPa
No.	Parameters	Depth of carbonation in mm			
<b>1</b>	<b>Civil engineering structures</b>				
<b>1a</b>	Exposed to rain		60.374	35.777	24.597
<b>1b</b>	Sheltered from rain		147.580	98.387	60.374
<b>1c</b>	In ground		24.597	17.889	11.180
<b>1d</b>	Under groundwater level		4.472	4.472	4.472
<b>2</b>	<b>Buildings</b>				
	<i>Outdoors</i>				
<b>2a</b>	Exposed to rain	122.984	60.374	35.777	24.597
<b>2b</b>	Sheltered from rain	245.967	147.580	98.387	60.374
	<i>Indoors in dry climate</i>				
	*				
<b>2c</b>	With cover (Paint or wall paper)	259.384	154.289	102.859	60.374
<b>2d</b>	With cover (Under tiles, parquet and laminate)	0.000	0.000	0.000	0.000
<b>2e</b>	Without cover	368.951	221.371	147.580	84.971
<b>2f</b>	In ground		24.597	17.889	11.180

### 5.3.5 Future supporting software development for an IVL Tier 3 model

For an IVL Tier 3, the design of the software (computer model) can be determined by the respective provider. However, the software must maintain high quality and be built on a scientific basis taking into account the experience in the field both nationally and internationally. The software must be objective, neutral, and calculate the CO<sub>2</sub> uptake values as accurately as possible with lowest possible uncertainty. Used methods and software should be transparent so that there is a possibility to conduct a scientific review of the entire system. The software must also be able to calculate the CO<sub>2</sub> uptake for a specific country or region, and it should also be specifically adapted to the respective geographical area. Furthermore, the software should also take into account as many as possible or most of the different aspects that affect the uptake of CO<sub>2</sub> in different concrete structures. Preferably, the software should also be based on the uptake of CO<sub>2</sub> in the actual calculated uptake areas based on historical data of annual amounts of clinker/cement or concrete used. Example of such methodology and models can be found in the peer reviewed articles [2] and [4]. Below is a list of aspects or data for CO<sub>2</sub> uptake in concrete or other cement-containing products that the software should be able to take into account and thus include in the model.

- Annual use of clinker/cement/concrete in the calculation region including historical data from the beginning of the time when cement began to be used. However, uptake data from primary products older than 100 years can normally be neglected as the CO<sub>2</sub> uptake is very slow. The use should be calculated as (production-export+import) for the region.
- The use of additions such as blast furnace slag, fly ash, silica fume, and limestone including also specific CO<sub>2</sub> uptake values for each material.
- If the use of additions in concrete is substantial and has a significant impact on the CO<sub>2</sub> uptake, the IVL Tier 3 method shall always be used.
- Emissions from the calcination of the materials in the cement kiln and check for the inclusion of emissions from additions for the corresponding year in the originating processes for the additions.
- Corresponding uptake areas for CO<sub>2</sub> in concrete structures or other cement-containing products, e.g. from the distribution in primary use for different concrete products and its area/volume ratio.
- Concrete surface environment when used in various products (porosity (w/c), temperature, indoors, outdoors, moisture, exposed to rain, underground, underwater, or surface treatment such as paint, wallpaper, asphalt/bitumen, etc.).
- Rate of carbonation including the square root of time dependence except for covered surface where a polynomial is more accurate.
- The sum of the cement content in the produced concrete should always be checked against the cement production.
- End-of-life processes for concrete or other uptake products during the calculation period including historical data. This shall include amount of concrete for demolition, type of handling (e.g. crushing, storing). How crushing into smaller fragments will increase the uptake surfaces and thereby the carbonation rate. Calculation of CO<sub>2</sub> uptake in the end-of-life process.
- Production and use of secondary products. Amount of concrete to secondary use products and its yearly CO<sub>2</sub> uptake, also for historical data.
- Landfill and use of remaining amounts and its CO<sub>2</sub> uptake. The CO<sub>2</sub> uptake in all end-of-life material must be included.

## 5.4 IVL Tier 2 model for annual CO<sub>2</sub> uptake - Advanced methodology II

### 5.4.1 Proposed CO<sub>2</sub> uptake model for IVL Tier 2

The present model, representing IVL Tier 2, provides a less advanced calculation method for estimating the annual uptake of CO<sub>2</sub> in existing concrete structures on a national basis than the IVL Tier 3. The model gives the option of calculating annual uptake in the primary use stage (existing structures) on the basis of the last few years/decades of cement clinker consumption for situations where the consumption has been rather stable over the years (Advanced methodology II, also referred to as Onward calculation method), whereas countries with less stable historical cement



clinker use should base the calculation on the same principles as the IVL Tier 3 model (Chapter 5.3), i.e. carbonation in existing concrete structures over the last 100 years (Advanced methodology I).

The proposed methodology for IVL Tier 2 includes simplified options for calculating carbonation in end-of-life stage (demolition, crushing, stockpiling), and the secondary use (recycling) compared to the IVL Tier 3 method.

The model should be used primarily in cases where resources are missing to perform a more accurate calculation according to the calculation methods described for IVL Tier 3 of Chapter 5.3, yet it has the potential and knowledge to perform a more advanced and improved CO<sub>2</sub> uptake model than the simplified model offered in IVL Tier 1. According to IPCC guidelines, Tier 2 or Tier 3 should also replace Tier 1 if the uptake in the country is defined as a “key category”.

#### 5.4.1.1 Primary use stage - Advanced methodology II

In Advanced methodology II, the mean value of the preceding 20 years of cement clinker consumption may be used together with knowledge of one year of concrete use and its distribution on different type of concrete structures. The mean value of the cement clinker consumption should normally be easy to access and would give a better estimation of the amounts of carbonating structures than only the last year’s consumption. In the international reporting, it is common to calculate the emissions/uptake for all years back to 1990. In the calculation of CO<sub>2</sub> uptake for year 1990, data from year 1970 thus should be used. Thus, a relatively long uptake period is included covering most of the fluctuations in cement clinker use for the countries. For a country with rather stable annual cement use, it is anticipated that the uptake during one year in existing buildings is equal to the uptake over the next (100) years in the concrete produced during the same year. For more information about this “onward” calculation method, see Chapter 5.4.3.2.1. This also means that if large variations in the use of concrete in previous years occur, e.g. if the concrete use started late in a country, the assumed uptake can deviate significantly from the assumption of the method. In such cases, Advanced methodology I should be used (see Chapter 5.3 for more guidance) and the CO<sub>2</sub> uptake in primary products should be based on the preceding 100 years cement clinker use, see Chapter 5.2.

A suggested general description of the required steps in the proposed Advanced methodology II is presented below, based on parts of the Swedish study [2] above and the paper by C. Andrade [9].

- Identify typical concrete applications (frequent type of structures). Normally, at least 5 applications should be needed, corresponding to at least 65 % of the cement consumption. For instance: Bridges, residential buildings, office buildings, roof tiles, pavement, shotcrete, sleepers, and mortar/render/plaster. Applications outside the chosen ones are treated as the most similar of the defined ones.

Cement clinker content, concrete quality, exposure, and surface area is described for each application. Usually, the data for each application can be obtained either from knowledge of the yearly concrete volume in each application and typical concrete mixture proportions for those applications or by knowing the cement clinker amounts and corresponding total concrete volumes for each application.

- Calculate the CO<sub>2</sub> uptake for each application as a function of time:

The CO<sub>2</sub> uptake in kg for each application during t years can be calculated as:  
(The formula can be found in EN 16757, Annex BB, equation BB.7. [16])

$$\text{CO}_2\text{-cumulative uptake} = (\Sigma(k_i \times \text{DOC}_i \times A_i)) (\sqrt{t}/1000) \times U_{\text{tcc}} \times C$$

Where

**CO<sub>2</sub>-uptake** is the total cumulative CO<sub>2</sub> uptake in kg CO<sub>2</sub> during t years in the application.

**k<sub>i</sub>** is a constant factor for the rate of carbonation for surface i in mm/√(t).

**DOC<sub>i</sub>** is the degree of carbonation for surface/volume i.

**A<sub>i</sub>** is the area of surface i in m<sup>2</sup>.

**t** is the number of years from start of carbonation.

**U<sub>tcc</sub>** is the maximum theoretical uptake in kg CO<sub>2</sub>/kg cement or clinker. The value is ≈ 0.49 for Portland cement (CEM I) and ≈ 0.52 for cement clinker.

**C** is cement content e.g. CEM I, otherwise clinker content in kg cement or clinker/m<sup>3</sup> of concrete.

Concrete quality, exposure, and surface area for the different parts of the application are determining the content of the first brackets. If the cement clinker content C varies between different parts of the application, the uptake must be calculated for each part and summed up. Values of k can be found in EN 16757, Annex BB [16] and in Table 26 below. The column ≤ 15 MPa in the table, can also represent mortar, render and plaster. Correction factors for k for cement with additional major constituents or concrete with mineral additions can be found in table BB.2, Table 27. Values of DOC can, for example, be found in EN 16757, Annex BB [16] and is also given in Table 26.

**Table 26** Table with k-factors for calculation of depth of carbonation for different strength classes (cylinder) and exposure conditions and also degree of carbonation for different exposure conditions. This table is reproduced from Annex BB of European standard EN 16757:2017, [16].

	Concrete strength	≤ 15 MPa*	15-20 MPa	25-35 MPa	≥ 35 MPa	Degree of carbonation (DOC)
No.	Parameters	Value of k-factor, in mm/year <sup>0.5</sup>				Percentage
<b>1</b>	<b>Civil engineering structures</b>					
1a	Exposed to rain		2.7	1.6	1.1	85
1b	Sheltered from rain		6.6	4.4	2.7	75
1c	In ground *		1.1	0.8	0.5	85
1d	Under groundwater level		0.2	0.2	0.2	85
<b>2</b>	<b>Buildings</b>					
	<u>Outdoor</u>					
2a	Exposed to rain	5.5	2.7	1.6	1.1	85
2b	Sheltered from rain	11	6.6	4.4	2.7	75
	<u>Indoor in dry climate **</u>					
2c	With cover (Paint or wallpaper)	11.6	6.9	4.6	2.7	40
2d	With cover (Under tiles, parquet and laminate)	0	0	0	0	0
2e	Without cover	16.5	9.9	6.6	3.8	40
2f	<u>In ground ***</u>		1.1	0.8	0.5	85

\* The k-factors in this column also represent mortar, render and plaster. Render and plaster usually is applied in layers with a total thickness of about 15-25 mm.

\*\* Indoor in dry climate means that the RH is normally between 45 and 65 %.

\*\*\* Under groundwater level k = 0.2

**Table 27** Correction for the k-factor for cement/clinker with additional major constituents or concrete with mineral additions. This table is reproduced from Annex BB of European standard EN 16757:2017 (Table BB.2), [16].

Amount of addition (weight %)	≤ 10	10 to 20	20 to 30	30 to 40	40 to 60	60 to 80
Limestone		1.05	1.1			
Silica fume	1.05	1.1				
Fly ash		1.05		1.1		
Ground Granulated Blast Furnace Slag (GGBS)	1.05	1.1	1.15	1.2	1.25	1.3

For other cement types than Portland cement (CEM I) and concrete with mineral additions the k-factors should be increased due to higher carbonation rate according to recommendation in EN 16757, Annex BB, table BB.2. If several additions are used in the concrete, the highest of the applicable correction factors shall be used. The correction factor adjusts the carbonation rate of the specific concrete. The total CO<sub>2</sub> uptake will be achieved by combining this new carbonation rate with the

maximum CO<sub>2</sub> uptake for the cement with the addition (kg CO<sub>2</sub>/kg cement) and the degree of carbonation (DOC). However, the correct CO<sub>2</sub> uptake figures for additions can be difficult to obtain.

Examples of calculation of CO<sub>2</sub> uptake in an application can be found in EN 16757, Annex BB, example 5 and 6.

- Calculate the last 20 years mean annual cement clinker consumption and estimate the annual concrete production and the cement clinker distribution on the different applications.
- Calculate the CO<sub>2</sub> uptake for each application for 100 years. (normally)
- Calculate the sum of the annual CO<sub>2</sub> uptake of all concrete applications.
- The sum of the cement content in the produced concrete should always be checked against the cement production.

For mortar/render/plaster or very thin applications, as for instance roof tiles, where total carbonation and maximum CO<sub>2</sub> uptake will occur in a few years, the CO<sub>2</sub> uptake can be calculated as

$$0.75 \times U_{\text{fcc}} \times C \text{ in kg CO}_2/\text{m}^3.$$

#### 5.4.1.2 End-of-life stage (demolishing, crushing and storage)

In the IVL Tier 1 - Simplified methodology - below, we introduce a conservative “default” value for this phase based on the present normal handling procedures of demolished and crushed concrete. These procedures normally include storage in large unsheltered piles, during a rather short period of time. Moreover, the recycling rate (the annual amount of demolished and crushed concrete in relation to the annual production) is normally low in most countries. The volumes can however be anticipated to increase in the future, as more concrete structures reach the end of their service life. It is therefore important to base CO<sub>2</sub> uptake calculations on the actual amounts of concrete that goes to end-of-life handling.

**The following estimations for CO<sub>2</sub> uptake in the end-of-life stage can be given.**

**For normal handling procedure or recycling rate less than 5 %:  
(Same as for Simplified methodology, IVL Tier 1)**

**If the annual amount of concrete in the end-of-life stage is known (m<sup>3</sup> per year), the uptake can be calculated as 10 kg CO<sub>2</sub>/m<sup>3</sup> of concrete.**

**If the annual amount of concrete in the end-of-life stage is not known, the uptake can be conservatively calculated as 2 % of the annual calcination emissions, (factor 0.02).**

**For improved handling procedure:**

**A preliminary suggestion is that the uptake could be set to 20 kg CO<sub>2</sub>/m<sup>3</sup> of concrete if an enhanced procedure with air access in the fractions and at least 4 months storage in at least three fractions is applied. In this case, the amount of concrete need to be known.**

### 5.4.1.3 Secondary use

Only very small amounts of concrete structures that have reached their service life, ends up as waste (landfill), but are used in crushed form as, or in, a new product – secondary use. It is therefore important to base the uptake calculations on the real amounts of concrete to secondary use. The CO<sub>2</sub> uptake in secondary use is quite similar to the uptake in primary use, so similar calculation methods could be used. However, even more factors are unknown for secondary use, so it can be difficult to create general but accurate methods. The more exact methods are often quite specific and depend on the type of secondary use (country specific) and may be treated under IVL Tier 3 in Chapter 5.3. Here, a more general method is proposed.

Under favourable conditions for the secondary use applications, the total uptake (primary use + end-of-life + secondary use) can amount to about 75 % ([11], [16]) of the maximum theoretical potential (equal to the calcination emission), corresponding to about 110 kg CO<sub>2</sub>/m<sup>3</sup> for an average concrete.

**As a lowest level for secondary use, an uptake according to the Simplified method (IVL Tier 1) can be used.**

**That is:**

**If the annual amount of concrete entering the secondary use is known (m<sup>3</sup> per year), the uptake can be calculated as 10 kg CO<sub>2</sub>/m<sup>3</sup> of concrete. This value is valid for unbound applications of crushed material. (If the annual amount of concrete entering the secondary use is not known, the uptake can be conservatively calculated as 1 % of the annual calcination emissions, factor 0.01.)**

### 5.4.1.4 Cement constituents and concrete additions

Different cement constituents and concrete additions are frequently used in different parts of the world, but the degree of use varies considerably between different manufacturers and countries. The materials used are also very different and their ability to bind CO<sub>2</sub> is also very different. The additions that are mainly used are ground granulated blast furnace slag (GGBS), fly ash, silica fume, and limestone. Relatively few data are available for the uptake of CO<sub>2</sub> in different additions, but some data, especially for blast furnace slag (GGBS), exist. In the first version of the IVL Tier 2 model used here, the correction factors of the carbonation rate factor ( $k_i$ ) from the standard EN 16757, Annex BB (Table 27) has been used when additions are used in the concrete. For a more accurate calculation, the maximum CO<sub>2</sub> uptake in the cement with addition/concrete needs to be known and used. A more detailed model for CO<sub>2</sub> uptake in various additions can then be made in IVL Tier 3. In IVL Tier 3, specific CO<sub>2</sub> uptake values for different additions can be obtained and used in the models.

A proposed simplified value for CO<sub>2</sub> uptake in GGBS has been developed as follows:

A proposed CO<sub>2</sub> uptake value for ground granulated blast furnace slag (GGBS) can be 25 kg CO<sub>2</sub>/tonne GGBS, see further Chapter 5.4.8.

The following chapters explain the background and consideration that underlie the proposed model.

## 5.4.2 Introduction

The Advanced methodology (AM), IVL Tier 2 or IVL Tier 3, should be used to make a better estimate of the annual CO<sub>2</sub> uptake than with the Simplified methodology (SM), IVL Tier 1. As mentioned before, it normally gives a more accurate uptake than the simplified one, thus encouraging the extra effort.

To be able to make a good estimate of the annual CO<sub>2</sub> uptake, one needs a good overview and knowledge of the existing concrete product stock in the country or region in question, since it is in these structures that the uptake takes place.

There is of course a correlation between the cement clinker consumption and the concrete production. The best way to obtain a historical estimate of the concrete production is normally via the cement clinker consumption, whose statistics are often available. For the Advanced methodology, it is essential that the sum of the cement clinker content in the produced concrete is checked against the cement consumption. The cement clinker consumption includes cement clinker production as well as import and export of cement clinker.

The basis for the Advanced methodology (as well as for the Simplified methodology) is accordingly the cement clinker consumption. Here, we should however have knowledge of, not only the consumption of the year in question, but a historical view going at least 20 years back in time in order to have a reasonable picture of the volume of the concrete production and thus the concrete product stock.

In lack of historical cement clinker data, in line with the IPCC Guidelines, extrapolation, expert judgement, and other quantification methods may be used to quantify relevant time series (see Chapter 5.2).

## 5.4.3 The primary use stage, results from different studies

The distribution of the cement consumption on different applications, for instance infrastructure, residential buildings, and other buildings, with typical surface/volume ratio and concrete quality, should be known. It has been shown [2] that it might be sufficient to know this distribution, not every year, but on a couple of occasions. Since the CO<sub>2</sub> uptake takes place in concrete produced during a long time, the relative changes in cement clinker distribution for different applications, due for instance to economic reasons, seem to even out in the long run. It is thus likely more important to have a detailed knowledge of the cement clinker distribution on different applications and products and of their exposure and surface/volume ratio on one occasion, than a vague picture on many occasions.

The different methods listed in the table “Characterization of existing models...in Appendix 1, Table 31” have somewhat different approaches to the estimation of the annual CO<sub>2</sub> uptake. They are below arranged under two headlines, Advanced methodology I and II.

Two of the methods estimate the annual uptake in the existing building stock by using extensive knowledge of the historical cement use, (Advanced methodology I). These two are also the base for the IVL Tier 3 method in Chapter 5.3.

Five of the methods estimate the annual uptake in the concrete product stock by using the assumption that the uptake during one year in concrete that was produced during the previous (100) years, which is the desired information, can be placed on an equality with the uptake the coming (100) years in concrete produced during the same year, (Advanced methodology II). This is referred to as the “Onward calculation method”. The uptake in the existing concrete product stock during a specific year (the reporting year) is what is requested. This uptake can be calculated by using knowledge of the historical concrete production (100 years if possible) as in Advanced methodology I. This knowledge is, however, often not at hand and the uptake calculation is also laborious. One can instead make use of the assumption that this “true” uptake value can be estimated by the uptake the coming (100) years in concrete produced the same year (the reporting year). The accuracy of this estimation largely depends on the stability of concrete usage over time. See further Chapter 5.4.3.2.1.

The table below is a short survey of the six different methods and compared with the IVL Tier 1A and IVL Tier 1B (see Chapter 5.5).

**Table 28** The table shows the different calculation principles for the different country specific CO<sub>2</sub> uptake models compared to IVL Tier 1A (Mean) and IVL Tier 1B (Mean – St. dev.).

Country/method	Advanced methodology I	Advanced methodology II	Simplified methodology IVL Tier 1A Relative values	Simplified methodology IVL Tier 1B Relative values
Sweden	Yes		84 %	65.5 %
Norway		Yes	112 %	88 %
The Netherlands		Yes	86 %	64 %
Ireland		Yes	125 %	94 %
Global	Yes		106 %	87 %
Switzerland		Yes	133 %	100 %
Spain		Yes	133 %	100 %

The seven methods in both Advanced methodology I and II have a similar approach when it comes to knowledge of cement distribution on different concrete applications/products. That is their relative amount, exposure, mean surface/volume ratio, concrete quality, and cement content. The CO<sub>2</sub> uptake of each application is calculated using k-factors and the same kind of square root of time dependency. Value of degree of carbonation may differ.

#### 5.4.3.1 The Advanced methodology I type used in previous studies

**The Swedish method** [2] uses knowledge of 100 years cement consumption and 60 years of distribution on different applications and knowledge of how concrete structures are distributed throughout the building sector to estimate the stock of concrete applications. The k-values and the degree of carbonation are very similar to the ones in EN 16757 [16]. The uptake each year is calculated as the difference between two consecutive years and is summed up for all the 7 applications/products.

*Influence of uncertainties in the model*

The result is obtained by using the market distribution of the concrete applications valid for the year 2010. A calculation based on actual historical statistics between 1950 and 2010 shows very similar results. The results show a dependence on the concrete quality, which is expected. If hypothetically all concrete would be of 45 MPa, the uptake would be reduced from about 300 to 170 ktonne. With 25 MPa, the uptake would increase to 470 ktonne. In practice, these extreme cases will not occur. Applying different lengths of service life (70-100 years) only results in minor changes to the uptake. The model input data, which consist of cement production and cement use in various products as well as cement types and concrete qualities, has both high availability and good reliability in most countries. The model has been designed to be robust to historical variations. The quality of the results is mainly influenced by the quality of the input data and its statistical distribution for the most recent year, compare [21].

This way of calculating could be characterized as an extra advanced methodology, where concern is taken to the historical cement/concrete production for 100 years, and also the distribution of cement on different applications is known under 60 years. The calculation should give a very good estimate of the annual uptake. With this methodology, it has been estimated that the CO<sub>2</sub> uptake in Sweden during the year of 2011 amounted to 300 000 tonne.

*Comparison with Simplified methodology IVL Tier 1A*

If the Simplified methodology would be used, the result would be:

Calcination emission 455 kg CO<sub>2</sub>/tonne cement (A mixture of CEM I and CEM II/A)

Cement consumption: 2.4 million tonne

CO<sub>2</sub> uptake is  $0.23 \times 0.455 \times 2\,400\,000 = 251\,160$  tonne, corresponding to 83.7 % of the advanced methodology value.

*Comparison with Simplified methodology IVL Tier 1B*

If the Simplified methodology would be used, the result would be:

Calcination emission 455 kg CO<sub>2</sub>/tonne cement (A mixture of CEM I and CEM II/A)

Cement consumption: 2.4 million tonne

CO<sub>2</sub> uptake is  $0.18 \times 0.455 \times 2\,400\,000 = 196\,560$  tonne, corresponding to 65.5 % of the advanced methodology value.

**The global method** [4] The data is provided for different regions (China, US, Europe and rest of the world). Degree of carbonation is set to 80 % in concrete and 92 % in average of mortar/render/plaster. The method uses 83 years (1930 – 2013) of cement consumption and a variety of regional information on concrete applications. The CO<sub>2</sub> uptake in the relation to the calcination emissions is given as a mean value for the 83 years, being 43 %, and for the year 2013, being 44 %. To be noted is the high share of cement for mortar/render/plaster application; 30 % is used in this application, and the uptake share is 70 %, due to the high surface/volume ratio and relatively low quality of the mortar/render/plaster. The uptake during the year 2013 is reported to be 0.24 Gt C, corresponding to  $(44/12) \times 0.24 = 0.88$  Gt, or 880 million tonne of CO<sub>2</sub>. This figure includes the end-of-life stage. The calcination emission during 2013 is reported to be 0.55 Gt C, corresponding to 2.02 Gt CO<sub>2</sub>.



Comparison with Simplified methodology IVL Tier 1A

With the suggested Simplified methodology, the uptake should have been:  
(With 30 % in mortar/render/plaster applications.)

The uptake factor is  $0.20 + 0.0115(30 - 10) + 0.02 + 0.01 = 0.20 + 0.23 + 0.02 + 0.01 = 0.46$ .

CO<sub>2</sub> uptake is  $0.46 \times 2\,020 = 929$  million tonne, corresponding to  $929/880 = 106\%$  of the advanced methodology value.

Comparison with Simplified methodology IVL Tier 1B

With the suggested Simplified methodology, the uptake should have been:  
(With 30 % in mortar/render/plaster applications.)

The uptake factor is  $0.15 + 0.01(30 - 10) + 0.02 + 0.01 = 0.15 + 0.20 + 0.02 + 0.01 = 0.38$ .

CO<sub>2</sub> uptake is  $0.38 \times 2\,020 = 768$  million tonne, corresponding to  $768/880 = 87\%$  of the advanced methodology value.

### 5.4.3.2 The Advanced methodology II type used in previous studies

Other methods in the country overview make use of the assumption that the uptake during one year in concrete that was produced during the previous (100) years, which is the desired information, can be placed on an equality with the uptake the coming (100) years in concrete produced during the same year. This can be characterized as “onward” calculation, which is further explained in Chapter 5.4.3.2.1.

For a 100 % identity, it is required unchanged production of cement and concrete and distribution on applications during the previous years. In practice, this unrealistic requirement can however be modified.

To be noted is that the years immediately prior to the reported year are most important for the uptake amount. This results from the square root of time dependency of the carbonation rate, which means that the concrete production of remote years becomes less important.

The Norwegian method [3]

The degree of carbonation is set to 70 % all over. The Norwegian report doesn't make any calculation based on historical values of cement consumption. The output of the model is the total amount of CO<sub>2</sub> bound by concrete consumed in Norway in 2011, assuming an onward service life of 100 years. It is anticipated that the uptake during one year in existing buildings is equal to the uptake over the next 100 years in the concrete produced for one year. Thus, in this case, only the production of cement and concrete applications for one year need to be known.

With this method, it is estimated that the annual uptake during 2011 in Norway is 140 000 tonne in the service life and 165 000 tonne if 100 years of “recovery phase” (secondary use) is added. In total, an uptake of 305 000 tonne CO<sub>2</sub>.

(It is however also reported that the uptake is 94 kg, resp. 111 kg CO<sub>2</sub>/tonne cement. With the annual cement consumption being  $\approx 1\,800$  ktonne, it means an annual uptake of 171 000, resp. 202 000 tonne. The apparent inconsistency depends on that the CO<sub>2</sub> uptake is calculated on basis of the actual concrete consumption, which corresponds to a “fictive” cement consumption of  $\approx 1\,500$  ktonne.)

From the Norwegian report, it can be found that three different cements (CEM I, CEM II/A-V and CEM II/B-S) have been used. The maximum CO<sub>2</sub> binding 2011 (70 % of the calcination emissions) is respectively 215, 252, and 55 thousand tonne of CO<sub>2</sub>, in total 557 000 tonne. The calcination emissions are accordingly  $557\ 000/0.70 = 795\ 000$  tonne.

Comparison with Simplified methodology IVL Tier 1A

With the suggested Simplified methodology, we should get in the use stage:

$0.20 \times 795\ 000 = 159\ 000$  tonne bound in the clinker

The GGBS amount in the CEM II/B-S (33 % GGBS) is  $0.33 \times 186\ 000 = 61\ 000$  tonne.

The uptake will accordingly be  $61\ 000 \times 0.035 = 2135$  tonne (35 kg CO<sub>2</sub>/tonne of GGBS, compare 5.4.8, last paragraph)

Total uptake in the use stage by the simplified method is 161 135 tonne compared to 140 000 tonne with the Advanced methodology (115 %).

The End-of-life stage and secondary use would add an extra  $0.03 \times 795\ 000 = 23\ 850$  tonne to the uptake, in total 185 000 compared to 165 000 with the Advanced methodology (112 %).

Comparison with Simplified methodology IVL Tier 1B

With the suggested Simplified methodology, we should get in the use stage:

$0.15 \times 795\ 000 = 120\ 000$  tonne bound in the clinker

The GGBS amount in the CEM II/B-S (33 % GGBS) is  $0.33 \times 186\ 000 = 61\ 000$  tonne.

The uptake will accordingly be  $61\ 000 \times 0.025 = 1\ 500$  tonne (25 kg CO<sub>2</sub>/tonne of GGBS)

Total uptake in the use stage by the simplified method is 121 500 tonne compared to 140 000 tonne with the Advanced methodology (86 %).

The End-of-life stage and secondary use would add an extra  $0.03 \times 795\ 000 = 23\ 850$  tonne to the uptake, in total 145 350 compared to 165 000 with the Advanced methodology (88 %).

**The Dutch method** [20]

The amount of GGBS in the different applications/products is provided. It is assumed that there is no change in the yearly concrete volume, composition, and applications. The production of cement and concrete of the year 2015 is taken as basis for the calculations. The CO<sub>2</sub> uptake in the use stage is 365 000 tonne. The CO<sub>2</sub> uptake in the “recycling stage” (end-of-life stage) is 83 000 tonne.

The “CO<sub>2</sub> emissions due to cement consumption” is 1 960 000 tonne. It is not quite clear, but it can be derived from the reasoning below, that this figure includes both CO<sub>2</sub> from calcination and fuel combustion. The cement consumption is 4 000 000 tonne and the average CO<sub>2</sub> emission per tonne cement is reported to be 0.49 tonne/tonne,  $4\ 000\ 000 \times 0.49 = 1\ 960\ 000$  tonne. The slag content is said to be 36 %. If the rest is assumed to be clinker, we have a clinker consumption of  $0.64 \times 4\ 000\ 000 = 2\ 560\ 000$  tonne (and a slag consumption of  $0.36 \times 4\ 000\ 000 = 1\ 440\ 000$  tonne). The corresponding calcination emission can be estimated at  $0.515 \times 2\ 560\ 000 = 1\ 318\ 000$  tonne CO<sub>2</sub>. This leaves only  $1\ 960\ 000 - 1\ 318\ 000 = 642\ 000$  tonne CO<sub>2</sub> for the fuel part, which can be reasonable since CO<sub>2</sub> neutral fuels are used to a large extent<sup>4</sup>.

---

<sup>4</sup> Personal communication with Edwin Vermeule: A lot of secondary fuels are used in the Netherlands (> 80 %). Those fuels are, to a large extent, CO<sub>2</sub>-neutral.

Comparison with Simplified methodology IVL Tier 1A

The Simplified methodology gives an uptake of  $0.20 \times 1\,318\,000 = 263\,600$  tonne, plus the uptake in the GGBS  $0.36 \times 4\,000\,000 \times 35 \times 0.001 = 50\,400$  tonne.

In total 314 000 tonne, corresponding to 86 % of the Advanced value.

Comparison with Simplified methodology IVL Tier 1B

The Simplified methodology gives an uptake of  $0.15 \times 1\,318\,000 = 198\,000$  tonne, plus the uptake in the GGBS  $0.36 \times 4\,000\,000 \times 25 \times 0.001 = 36\,000$  tonne.

In total 234 000 tonne, corresponding to 64 % of the Advanced value.

**The Irish method** [5]

The carbonation rate for each application is calculated using a calibrated Irish formula from Silva et al. [15]. The degree of carbonation is not specified. For the year 1972, the calcination emissions are estimated to have been 780 000 tonne and the concrete produced that year is estimated to have taken up 98 000 tonne by the end of year 2013 (40 years), corresponding to 13 %. On a 100 years perspective, this should have increased to about  $13 \sqrt{(100/40)} = 20$  %. The report says 16 %. The figure 16 % is used in the statistical calculation for the Simplified methodology. It also mentioned that this figure corresponds to an uptake of 75 kg CO<sub>2</sub>/tonne cement over 100 year service life. With a mean cement consumption of about 2 000 ktonne, it means an annual uptake in Ireland of about 150 000 tonne.

An estimate of the cement use in Ireland over last 40 years has been done, but it is not clear if these historical year-by-year values have really been used in the calculations. The uptake during one year in the existing buildings is not explicitly reported, but if it anticipated that it is approximately equal to 100 years of uptake in one year production, the value of 16 %, or 75 kg/tonne cement, can be used.

Comparison with Simplified methodology IVL Tier 1A

The Simplified methodology gives the uptake of 0.20 or 20 %, which in this case is more than the presented Advanced method value of 16 % ( $20/16 = 125$  %).

Comparison with Simplified methodology IVL Tier 1B

The Simplified methodology gives the uptake of 0.15 or 15 %, which in this case is very close ( $15/16 = 94$  %) to the presented Advanced method value of 16 %.

**The Swiss method** [13, 12].

The degree of carbonation is in the report [13] set to 75 % throughout, but is later in another paper [12] changed to 50 %. As in most reports, it is anticipated that the uptake during one year in existing buildings is equal to the uptake over the next (100) years in the concrete produced for one year. An average uptake of 10 % of the total emissions, for 50 years is presented in the report. For the calcination emissions, the figure can be estimated to be  $10 \times (1/0.63) = 16$  %. For 100 years, the figure can be estimated to be  $16 \times \sqrt{(100/50)} = 23$  %. With a degree of carbonation being 50 % instead of 75 % we get  $23 \times (50/75) = 15$  %.

(According to the Annex BB of the EN 16757 [16] the degree of carbonation varies between 40 % for indoor structures to 85 % for outdoor structures not sheltered from rain.)

Comparison with Simplified methodology, IVL Tier 1A

The figure 15 % is less than the Simplified methodology, IVL Tier 1A, value, which is 20 % ( $20/15 = 133$  %).

Comparison with Simplified methodology, IVL Tier 1B

The figure 15 % is the same as the Simplified methodology, IVL Tier 1B, value ( $15/15 = 100$  %).

**The Spanish method** [6,7,8, and 9]

The Spanish results are extensively discussed and dealt with under Chapter 5.5.3, resulting in the Spanish CO<sub>2</sub> uptake value being 15 % of the calcination emissions.

Comparison with Simplified methodology, IVL Tier 1A

The figure 15 % is less than the Simplified methodology, IVL Tier 1A, value, which is 20 % (20/15=133 %).

Comparison with Simplified methodology, IVL Tier 1B

The figure 15 % is the same as the Simplified methodology, IVL Tier 1B, value (15/15 = 100 %).

(This assumes that the Spanish value for comparison is the one updated by the C. Andrade paper [9] and the further calculation in Chapter 5.5.3.)

**5.4.3.2.1 The Onward calculation method**

To simplify the uptake calculations, it can be assumed in IVL Tier 2 (Advance methodology II) that the uptake of CO<sub>2</sub> the present year can be equated with the uptake of CO<sub>2</sub> for 100 years in the current distribution of concrete products and structures, and with the current year's concrete production. In reality, this year's uptake of CO<sub>2</sub> takes place in today's standing concrete products and structures, in concrete produced during the last 100 years. This approximation is relatively good provided that the concrete production has been fairly stable over the years. If greater variations in concrete production have occurred, this calculation method can be improved by using a rolling average value of the use of concrete or clinker over a longer period of time. However, for more accurate annual IVL Tier 2 calculations, Advanced methodology I should be used, taking preceding 100 years cement clinker use into account.

Five of the national methods estimate the annual uptake in the concrete product stock by using this assumption.

The uptake in existing concrete product stock during a certain year (the reported year) is what is to be calculated. This can be done by using knowledge of the historical concrete production (100 years if possible) as in Advanced methodology I. This knowledge is however often not at hand and the uptake calculation is also laborious. As an alternative, one can instead make use of the assumption that this "true" uptake value can be equivalent with the uptake the coming (100) years in concrete produced the same year (the reported year). This equality can be shown to be exact valid during certain circumstances and approximate valid during practical situations.

For an exact equality, it is required that the cement or rather concrete production has been almost equal the previous years and the actual year (the reported year). This means not only the amount and type of concrete but also the use of the concrete, i.e. the applications with their exposure and surface to volume ratio. See further explanation below \*).

In practice, some circumstances modify these stringent requirements. Due to the square root of time dependency of the carbonation rate, it follows that the remote years production is of less importance for the present uptake. Even if we count on 100 years of service life for concrete contributing to the CO<sub>2</sub> uptake, 20 years of production accounts for  $\sqrt{20}/\sqrt{100}=45$  % of the total uptake. Therefore, the requirement on similar production of concrete and applications can be limited to the last 20 years.

However, if the cement use is very different in previous years (e.g. 50 - 20 years ago), then it is recommended to use the Advanced methodology I in IVL Tier 3, taking preceding 100 years cement clinker use into account (see Chapter 5.2).

To improve the approximation, one could use the average value of concrete production during the last 20 years (for instance estimated through cement/clinker consumption, which is generally well reported) for the onward calculation of the uptake.

The relative changes in cement distribution for different applications, due for instance to market reasons, seem to even out in the long run. It is thus normally more important to have a detailed knowledge of the cement distribution on different applications and products and of their exposure and surface/volume ratio on one occasion, than a vague picture at many occasions.

These facts accordingly make the approximation of the onward calculation methodology (Advanced Methodology II) to be an acceptable calculation method.

\*) This follows from the equation for the CO<sub>2</sub> uptake.

$$\text{CO}_2 \text{ cumulative uptake} = (\Sigma(k_i \times \text{DOC}_i \times A_i)) (\sqrt{t}/1000) \times U_{\text{tcc}} \times C$$

where all the parameters (k, DOC, A, U<sub>tcc</sub> and C) are kept constant, their product being say P.

The uptake for the reported year, according to Advanced Methodology II, will, for 100 years, be  $P \times \sqrt{100}$ .

The uptake the reported year, according to Advanced Methodology I, will for 100 years of service life be:

$$P \times \Sigma(\sqrt{i} - \sqrt{i-1}), \text{ where } i \text{ goes from } 100 \text{ to } 1. \text{ The result is also } P \times \sqrt{100}.$$

(The uptake for the reported year is the difference between this year and the year before, summarized for all the previous years:  $(\sqrt{100} - \sqrt{99}) + (\sqrt{99} - \sqrt{98}) + \dots + (\sqrt{2} - \sqrt{1}) + (\sqrt{1} - \sqrt{0}) = \sqrt{100}$ .)

## 5.4.4 Discussion of “good practice” for the Advanced methodology in the Use stage

The Advanced methodology should be based on the uptake in the actual existing concrete product stock. To achieve this, we first need the historical cement use in a country or region in question. This information is known in some countries but not all. Moreover, in cases with rather stable cement use over the last decades, it might be enough to go 20 years back since the uptake is following a square root of time dependency. Even if we can count on 100 years of service life for concrete contributing to the CO<sub>2</sub>-uptake, the last 20 years production of this period accounts for  $\sqrt{20}/\sqrt{100} = 45\%$  of the total uptake the present year. The last 50 years production accounts for  $\sqrt{50}/\sqrt{100} = 71\%$ . Depending on the historical development of cement use and the degree of accuracy needed for the CO<sub>2</sub> uptake estimations, Advanced methodology I or II should be chosen accordingly.

Thus, what happened in the cement consumption and concrete production historically is of importance for the present uptake. Also, smaller production figures in the remote years, often make this period less important. However, when there is available statistics on cement consumption for a longer period, a more accurate estimation can be done, as in the Swedish method [2]. The historical cement clinker consumption together with data availability should thus be the driver for which Advanced methodology (I or II) to use.

As we have seen in the survey above, many countries rely only on one-year figures. The difference to the Simplified methodology (IVL Tier 1) lies in the necessary knowledge about concrete applications, of cement distribution on different applications/products. That is their relative amount, exposure, mean surface to volume ratio, concrete quality, cement content, k-values and degree of carbonation. The rate of carbonation for each application is calculated using k-values and the square root of time dependency. The k-values given in the EN 16757, Annex BB [16] for different exposures and concrete qualities have been found to be well balanced in many studies. The important factor degree of carbonation (DOC) can also be found in the EN 16757, Annex BB for different exposures or in Table 26.

The comprehensive earlier studies by Spain [6,7,8], compiled and adjusted in the recent paper by C. Andrade [9], includes many different types of cement, two types of concrete and three exposures, show that the DOC for indoor exposure is around 45 % and for outdoor exposure around 60 % for sheltered concrete and 80 % for not sheltered concrete (exposed to rain). (DOC is here expressed as the amount of CaO that has converted to CaCO<sub>3</sub> in relation to the original amount of CaO, or (which is the same) the amount of bound CO<sub>2</sub> in relation to the emitted CO<sub>2</sub> by calcination.) The Spanish figures, valid for Portland cement, are rather well in line with the ones presented in the EN 16757. The indoor is a bit higher (45 % compared to 40 %) and the outdoor is a bit lower (60 % or 80 % compared to 75 or 85 %).

### 5.4.5 The Advanced methodology I, based on wide historical data on cement and concrete use – an overview

Calculation method using historical data, according to, for instance, the Swedish and the Global studies [2,4], where the uptake each year is calculated as the difference between two consecutive years and is summed up for all the applications/products. Data from 100 years statistic of cement consumption (cement production-export+import) and knowledge of concrete use from at least three different and well-distributed years over the calculation period should be used.

For primary use stage, this methodology is the same as for IVL Tier 3 described in Chapter 5.3, however, with simplifications made on the product distribution and use of standard factors from EN 16757, Annex BB.

### 5.4.6 The Advanced methodology II, based on a single or few years data on cement and concrete use – an overview

In the Advanced methodology II the mean value of at least 20 years of cement consumption may be used together with knowledge of one year of concrete use. The mean value of the cement consumption should normally be easy to access and would give a better estimation of the amounts of carbonating structures than only the last year's consumption. It is anticipated that the uptake during one year in existing buildings is equal to the uptake over the next (100) years in the concrete

produced during the same year. Calculation method onwards, according to for instance the Norwegian study [3].

Both methods (AM I and II) require knowledge of cement consumption statistics and concrete production and use, but on a different level. The calculation as such is simpler with the second methodology. The result should be presented as annual amount of CO<sub>2</sub> uptake for a country or region.

A suggested general description of the required steps in the Advanced methodology II is presented below, based on parts of the Swedish study above and the article by C. Andrade [9]. A more comprehensive presentation is made in Chapter 5.4.1.1.

- Identify typical concrete applications (frequent type of structures). Normally, at least 5 applications should be needed, corresponding to at least 65 % of the cement consumption. For instance: Bridges, residential buildings, office buildings, roof tiles, pavement, shotcrete, sleepers, and mortar/render/plaster. Applications outside the chosen ones are treated as the most similar of the defined ones.

Cement content, concrete quality, exposure and specific surface (m<sup>2</sup> surface/m<sup>3</sup> concrete) is described for each application. Especially exposure and specific surface may vary within the application.

- Calculate the CO<sub>2</sub> uptake for each application as a function of time:

The CO<sub>2</sub> uptake in kg for each application during t years can be calculated as:

(The formula can be found in EN 16757, Annex BB.)

$$\text{CO}_2\text{-uptake} = (\Sigma(k_i \times \text{DOC}_i \times A_i)) (\sqrt{t}/1000) \times U_{\text{tcc}} \times C$$

Where

**CO<sub>2</sub>-uptake** is the total CO<sub>2</sub> uptake in kg CO<sub>2</sub> during t years.

**k<sub>i</sub>** is a constant factor for the rate of carbonation for surface i in mm/√(t).

**DOC<sub>i</sub>** is the degree of carbonation for surface/volume i.

**A<sub>i</sub>** is the area of surface i in m<sup>2</sup>.

**t** is the number of years from start of carbonation.

**U<sub>tcc</sub>** is the maximum theoretical uptake in kg CO<sub>2</sub>/kg cement or clinker. The value can be ≈ 0.49 for Portland cement (CEM I) and ≈ 0.52 for clinker.

**C** is cement content e.g. CEM I, otherwise clinker content in kg cement or clinker/m<sup>3</sup> of concrete.

(It is also possible to calculate an application with different U<sub>tcc</sub> or C, by giving them index i and put them in the Σ – parenthesis.)

Values of k can be found in EN 16757, Annex BB. See also Table 26.

Values of DOC can be found in EN 16757, Annex BB. See also Table 26.

Examples of this kind of calculation can be found in EN 16757, Annex BB, example 5 and 6.

- Calculate the last 20 years mean annual cement/clinker consumption and estimate the annual concrete production and the distribution on the different applications.

- Calculate the CO<sub>2</sub> uptake for each application for 100 years. (normally)
- Calculate the sum of the annual CO<sub>2</sub> uptake of all concrete applications.
- The sum of the cement content in the produced concrete should always be checked against the cement production.

## 5.4.7 End-of-life stage and secondary use

### 5.4.7.1 End-of-life stage (demolishing, crushing and storage)

In the Simplified methodology (IVL Tier 1), we introduced a conservative “default” value for this phase based on the present normal handling procedures of demolished and crushed concrete. These procedures include normal storage in large unsheltered piles during a rather short period of time.

Moreover, the recycling rate (the annual amount of demolished and crushed concrete in relation to the annual production) is normally low in most countries. The volumes can however be anticipated to increase in the future, since more concrete structures reach the end of the service life. This foreseen increase should however not be speeded up for CO<sub>2</sub> uptake reasons. The present normal handling procedures for storage of crushed material, awaiting secondary use, are however not focused on facilitating CO<sub>2</sub> uptake and here; improvements can and should be implemented.

The drawback with the normal handling is the large piles of crushed material of mixed sized fractions. Although the fine fractions carbonate rapidly near the surface of the stockpile, the mixed size fractions, exposed to rain, form a rather compact material that prevents the free air circulation into the bulk of the stockpile. Measurements have shown that only up to about 0.3 m from the surface is influenced by carbonation. Changing of the handling procedures comprise commercial considerations but can be very effective when it comes to CO<sub>2</sub> uptake.

In [17], there is an estimate that an enhanced processing of crushed concrete, implying 1-4 months storing in five fractions, can increase the uptake in the end-of-life stage to about 20 kg CO<sub>2</sub>/m<sup>3</sup> of concrete.

In the report [14], crushed concrete aggregates from waste hollow core slabs and decommissioned railway sleepers were analysed for their material characteristics. To investigate if graded crushed materials would have a better ability to absorb CO<sub>2</sub>, the two different concrete materials used in this study were sieved and placed outdoors and sheltered from rain. The concrete was crushed and graded into three sizes; 0-4, 4-8, and 8-16 mm and placed in pallet collars with a net at the bottom. The total depth of the material was 0.4 m. After 18 months, the material was tested at four levels; 0, 0.12, 0.24, and 0.36 m from the top surface. Both the degree of carbonation and the amount of cement paste in each fraction was measured.

It was found that the grading of the crushed concrete aggregates into the three size fractions improved the CO<sub>2</sub> diffusion into the cement paste and increased the CO<sub>2</sub> uptake in the aggregates compared to the uptake of ungraded material. The main portion of the cement paste accumulated in the 0-4 mm size fraction and this fraction also experienced the highest carbonation degree; 0.45 -0.65, but only in the outer layer. The inner layers carbonated at a lower rate, carbonation degree about 0.20, probably due to the higher gas diffusion resistance created by the finer particles. In the size fractions 4-8 and 8-16 mm, less gas diffusion resistance was experienced, and the carbonation degree was similar throughout the whole material.



From the given data on amount of cement paste and degree of carbonation of the different size fractions, it is possible to calculate the CO<sub>2</sub> uptake with the used storage conditions (18 months outdoors, sheltered from rain).

The cumulative grading curve of all the crushed material was not measured at the investigation but can be taken to be similar to a curve of crushed concrete presented in [17]. The following relative figures for the three fraction sizes are anticipated.

- 0 – 4 mm: 50 %
- 4 – 8 mm: 15 %
- 8 - 16 mm 35 %

In the 0 – 4 fraction, the “outer layer” constitute about 25 % (carbonation degree 0.55), and the rest about 75 % (carbonation degree 0.20). The uptake per m<sup>3</sup> of concrete, crushed into the three fractions, can be calculated as shown in Table 29. The total reported amount of paste in the three fractions is 378 kg/m<sup>3</sup>, where average quality concrete has original cement paste content of about 500 kg/m<sup>3</sup>. About 24 % (122/500) of the cement paste has been lost during the crushing and fractioning process, probably as fine dust.

**Table 29** Calculated CO<sub>2</sub> uptake after 18 months (outdoors, sheltered from rain) in crushed concrete (1 m<sup>3</sup>) separated into fractions, [14].

Size fraction (mm)	Relative amount	Paste		Cement* (kg)	Degree of carbonation (%)	CO <sub>2</sub> uptake** (kg CO <sub>2</sub> /m <sup>3</sup> concrete)
		(%)	(kg)			
0 - 4 outer	0.5 × 0.25	25	75	53	55	14
0 - 4 inner	0.5 × 0.25	25	225	158	20	15
4 - 8	0.15	10	36	25	25	4
8 - 6	0.35	5	42	29	30	4
<b>Total</b>	<b>1.0</b>		<b>378</b>	<b>265</b>		<b>37</b>

\* Paste, kg × 350/500. Cement 350 kg/m<sup>3</sup>, Water 150 kg/m<sup>3</sup>, w/c = 0.43 assumed (70 % of paste)

\*\* Cement × Degree of carbonation × 0.49

From Table 29, the CO<sub>2</sub> uptake for the three fractions after 18 months is 37 kg/m<sup>3</sup> concrete. If one assumes that the uptake is proportional to the square root of time, this corresponds to about 18 kg/m<sup>3</sup> concrete for 4 months storage.

Some part of the hardened cement paste will separate during the crushing process as very fine particles. With suitable handling, these very fine particles will rapidly carbonate, possibly in days but up to a few weeks. If about 20 % of the cement paste is falling in this very fine fraction, and the carbonation degree is 75 %, the resulting uptake for a concrete with CEM I-cement content of 300 kg/m<sup>3</sup> will be an extra  $0.2 \times 300 \times 0.49 \times 0.75 = 22$  kg CO<sub>2</sub>/m<sup>3</sup> of concrete.

(The amount of these very fine particles is depending on crushing and sieving equipment and not yet possible to estimate accurately.)

It is important to find some way of including a future larger uptake in the end-of-life stage and to give reporting opportunities for countries with an already high rate of recycling as for instance the Netherlands and Germany. For very long storage times, years or more, and small particles in fractionized piles of low thickness, an uptake of about 75 % ([11], [16]) of the maximum theoretical potential uptake can be expected, corresponding to about 110 kg CO<sub>2</sub>/m<sup>3</sup> of concrete.

The following estimations for CO<sub>2</sub> uptake in the end-of-life stage can be given.

**For normal handling procedure or recycling rate less than 5 %:**

(Same as for Simplified methodology, IVL Tier 1)

If the annual amount of concrete in the end-of-life stage is known (m<sup>3</sup> per year), the uptake can be calculated as 10 kg CO<sub>2</sub>/m<sup>3</sup> of concrete.

If the annual amount of concrete in the end-of-life stage is not known, the uptake can be conservatively calculated as 2 % of the annual calcination emissions, (factor 0.02).

**For improved handling procedure:**

A preliminary suggestion is that the uptake could be set to 20 kg CO<sub>2</sub>/m<sup>3</sup> of concrete if an enhanced procedure with air access in the fractions and at least 4 months storage in at least three fractions is applied. In this case, the amount of concrete needs to be known.

**The handling procedure for demolishing, crushing and storage, presented in [17], is an example of such improved procedure.**

#### 5.4.7.2 Secondary use

Only very small amounts of concrete structures that have reached their service life, actually ends up as waste (landfill), but are used in crushed form as, or in, a new product – secondary use. It is therefore important to base the uptake calculations on the real amounts of concrete to secondary use. The CO<sub>2</sub> uptake in secondary use is quite similar to the uptake in primary use, so similar calculation methods could be used. However, even more factors are unknown for secondary use, so it can be difficult to create general but accurate methods. The more exact methods are often quite specific and depend on the type of secondary use (country specific) and may be treated under IVL Tier 3 in Chapter 5.3. Here, a more general method is proposed.

In the Simplified methodology (IVL Tier 1), we introduced a conservative “default” value for this phase.

The annual amount of concrete presently being taken out of service and reused is, accordingly in most countries, small compared to concrete produced. The volumes can be anticipated to increase in the future, since more concrete structures reach the end of the service life.

For crushed material in secondary use, the estimation of the uptake is rather diverse, depending on the different possible applications such as

- Road base, filling material and similar unbound applications (large potential for carbonation).
- Aggregate for new concrete (limited potential for carbonation).

Uptake in these applications is also taking place in already, to some extent, carbonated material. (During the primary use and the end-of-life stage.)

The literature is rare on this subject.

Calculation of scenarios with different premises can give an estimation of reasonable uptake figures for these applications. To do this, we need however information about average carbonation status of the used crushed material, as well as carbonation rate of the new applications. This information is, so far, not available.

In [17], a theoretical discussion of a possible uptake in the secondary use is presented:

*“The use phase of the crushed material is calculated to a practical CO<sub>2</sub> maximum uptake. This uptake is thus reached in different time periods indicated in the comments. The use applications assume a relatively free access to air (CO<sub>2</sub>). For the fractions larger than 4 mm, this can probably be achieved by using the material as filling materials in different construction applications and leaving openings in the aggregate construction for air circulation. The smaller fractions (0-4 mm) have a relatively compact structure due a large share of very fine particles. This indicates that the material should be used in thin structures. Examples of this can be top surface layers or slip control on roads. The applications for high uptake of CO<sub>2</sub> are relatively new and further development work is required. The CO<sub>2</sub> uptake is estimated for each application based on aggregate size and type of application.”*

*“For large aggregates, it is important to keep in mind that CO<sub>2</sub> is only taken up by the cement paste and not the ballast materials. Larger aggregates can thus consist of a stone covered with cement paste. Usually the stone material is stronger than the cement paste so the crushing fractures occur in the cement paste leaving a stone with a relatively thin layer of cement paste. This means that the size distribution of the ballast used in the concrete can influence the CO<sub>2</sub> uptake. Thus, a relatively large aggregate can show a fast carbonation. The thickness of the cement paste layer is, in this case, of significant importance.”*

Also in [2], the large potential of uptake in secondary use applications is emphasized.

**As a lowest level for secondary use, an uptake according to the Simplified method (IVL Tier 1) can be used.**

**That is:**

**If the annual amount of concrete entering the secondary use is known (m<sup>3</sup> per year), the uptake can be calculated as 10 kg CO<sub>2</sub>/m<sup>3</sup> of concrete. This value is valid for unbound applications of crushed material. (If the annual amount of concrete entering the secondary use is not known, the uptake can be conservatively calculated as 1 % of the annual calcination emissions, factor 0.01.)**

Under favourable conditions for the secondary use applications, the total uptake (primary use + end-of-life + secondary use) can amount to about 75 % ([11], [16]) of the maximum theoretical potential (equal to the calcination emission), corresponding to about 110 kg CO<sub>2</sub>/m<sup>3</sup> for an average concrete.

## 5.4.8 Cement with different constituents or additions added at the concrete mixer

Different cement constituents and concrete additions are frequently used in different parts of the world, but the degree of use varies considerably between different manufacturers and countries. The materials used are also very different and their ability to bind CO<sub>2</sub> is also different. The additions that are mainly used are ground granulated blast furnace slag (GGBS), fly ash, silica fume, and limestone. Relatively few data are available for the uptake of CO<sub>2</sub> in different additions, but some data, especially for blast furnace slag, exist. It is therefore difficult to provide general recommendations for calculations of CO<sub>2</sub> uptake in additions, why a possibility is to include additions only when calculations are made using the IVL Tier 3 method in Chapter 5.3. In that case, the IVL Tier 3 method should be used when the use of additions is high in used concrete and if this affects the CO<sub>2</sub> uptake to a significant extent. However, the IVL Tier 2 model might be used if reactive content of CaO could be established for the used fly ash or GGBS, and accordingly an adjusted maximum theoretical CO<sub>2</sub> uptake can be calculated.

To improve and simplify the uptake calculations when additions are used in concrete, a simplified CO<sub>2</sub> uptake calculation method for additions can be used. In the first version of the IVL Tier 2 model used here, a correction factors of the carbonation rate factor ( $k_i$ ) from the standard CEN/EN 16757, Annex BB (Table 27) can be used when additions are used in concrete, in combination with an adjusted value of the maximum theoretical CO<sub>2</sub> uptake ( $U_{\text{teor}}$  kg CO<sub>2</sub>/kg cement) in the corresponding cement (including clinker and various additions). Note that additions to be included can be added to the cement or in the concrete production. A proposed simplified value for CO<sub>2</sub> uptake due to use

of ground granulated blast furnace slag (GGBS) in concrete can be found below. Below is also a brief technical information about CO<sub>2</sub> uptake in additions that can be used for the development work under IVL Tier 3.

One has to distinguish between two effects of the additions. One is fairly well established and that is the increased rate of carbonation. Adjustment factors for the rate of carbonation compared to Portland cement (CEM I) is found for instance in the EN 16757, Annex BB [16]. For concrete of the same strength, the factors show for instance that the rate of carbonation will increase with 25 % if a binder with 40 – 60 % of GGBS is used. The rate will increase with 5 % if a binder with 10 – 20 % of fly ash is used. The increased rate of carbonation does however not mean that the total CO<sub>2</sub> uptake will increase. The uptake is also depending on how much of the Ca(OH)<sub>2</sub> and other compounds in the carbonated zone of the concrete that is actually converted to CaCO<sub>3</sub>, (so called degree of carbonation).

GGBS, having a rather high CaO content, is the addition with the largest potential to take up CO<sub>2</sub>. It is a latent hydraulic binder and does not need to consume Ca(OH)<sub>2</sub> from the clinker hydration to react. The fly ash and especially the silica fume contain small amounts of CaO and need the Ca(OH)<sub>2</sub> from the clinker hydration to react. Since Ca(OH)<sub>2</sub> is normally the first component of the hydrated cement to carbonate, the addition of fly ash or silica fume, can theoretically decrease the amount of CO<sub>2</sub> uptake, even if the rate of carbonation will increase as mentioned above.

The limestone addition is normally used in amounts less than 20 %. The increase on rate of carbonation from that addition is 10 % or less. Only minor parts of the limestone participate in the hydration, so the uptake can be assumed to take part only in the clinker reaction products.

**To summarize:** We have a situation with increased carbonation rate, meaning larger volume of carbonated concrete. On the other hand, a decreased amount of CO<sub>2</sub> bound per volume in this carbonated concrete. This fact makes it reasonable that, for the estimation of uptake in the Simplified method, (IVL Tier 1), see Chapter 5.5.1, it is proposed that it is counted in the clinker only and the figure is based on the annual clinker calcination emission.

A solution with zero CO<sub>2</sub> uptake in the additions is also used in the EN 16757, Annex BB as a conservative estimation. An estimation based on clinker content only may, however, underestimate the CO<sub>2</sub> uptake if GGBS is used as additional constituent or addition. The problem is that there is, so far, not much knowledge of the CO<sub>2</sub> binding capacity of the GGBS hydration products. The attempts to estimations relate the uptake capacity to the amount of CaO, in the same way as with the clinker. The amount of CaO in GGBS is lower and varies more than in clinker.

In the **Norwegian report** [3], a calculation example is provided by which 70 % of the CaO in the GGBS can be carbonated. The amount of CaO in the GGBS is, in this case, 40 %. (The amount of CaO in the clinker is set to 65 %.) The additional uptake in the GGBS can be estimated to be  $0.70 \times 0.40 / 0.65 = 0.43$  or 43 % of the clinker uptake. Thus, if the maximum uptake in the clinker is 515 kg/tonne, the maximum uptake in the GGBS is  $0.43 \times 515 = 221$  kg CO<sub>2</sub>/tonne. It should be emphasized that the Norwegian report does not claim that the figure 70 % for the CaO that can be carbonated is reliable. The binding capacity depends on the hydration products of the GGBS and to which extent they will carbonate under the normal partial pressure of CO<sub>2</sub>.

We have earlier proposed that a conservative estimation is that 0.15 ( $0.15 \times 515 = 77$  kg CO<sub>2</sub>/tonne clinker) of the annual calcination emissions will be taken up, (or 0.15 of the maximum uptake). If we apply the same thinking on GGBS, then  $0.15 \times 221 = 33$  kg CO<sub>2</sub>/tonne GGBS will be taken up.

Note that for concretes with GGBS, the uptake per m<sup>3</sup> of concrete is normally smaller than the uptake of concrete without GGBS, due to the fact that the clinker content is reduced and that GGBS take up less CO<sub>2</sub> per mass than clinker, (less CaO content and less “reactive” CaO).

In the **Dutch report** [20], it is anticipated that the maximum CO<sub>2</sub> uptake in GGBS is 140 kg CO<sub>2</sub>/tonne GGBS. The maximum uptake in CEM I is 490 kg CO<sub>2</sub>/tonne cement, or 515 kg CO<sub>2</sub>/tonne clinker. A maximum CO<sub>2</sub> uptake of 140 kg per tonne GGBS will result in an uptake of  $0.15 \times 140 = 21$  kg CO<sub>2</sub>/tonne GGBS.

Without any more data than the values 221 and 140 kg/tonne for the maximum CO<sub>2</sub> uptake in the GGBS, or 33 and 21 kg/tonne for a conservative estimate of the uptake, it seems feasible to select a value of about 25 kg CO<sub>2</sub>/tonne GGBS for the annual uptake in concrete with GGBS if the methodology in IVL Tier 2 is used.

The value 25 kg CO<sub>2</sub>/tonne GGBS corresponds to the maximum emission value 166 kg CO<sub>2</sub>/tonne GGBS, which emanates from the blast furnace in the steel industry.

In line with the mean value factor 0.20 (see Chapter 5.5.3), the uptake in the GGBS can be estimated at  $0.20 \times 166 \approx 35$  kg CO<sub>2</sub>/tonne GGBS.

## 5.5 IVL Tier 1 model for CO<sub>2</sub> uptake - Simplified methodology

### 5.5.1 Proposed CO<sub>2</sub> uptake model for IVL Tier 1

The present model, representing IVL Tier 1, provides a simplified calculation method for estimating the uptake of CO<sub>2</sub> in existing concrete structures on a national basis. The calculations are based on the CO<sub>2</sub> emissions from the calcination of the corresponding amount of cement clinker used for the calculations. It can thus cover an optional period of time (e.g. annual) and different amounts of concrete. The model should be used primarily as a first estimate or in cases where resources are missing to perform more accurate calculations according to the calculation methods described for IVL Tier 2 and IVL Tier 3 of Chapter 5.4 and Chapter 5.3, since the uncertainty is likely higher for IVL Tier 1 as this is a simplified calculation method. The national annual CO<sub>2</sub> uptake in concrete; in the use stage (existing structures), in end-of-life stage (demolition, crushing, stockpiling), and in secondary use (recycling), can be estimated according to this Simplified methodology. The uptake values are related to the estimated calcination emissions from the annual consumed clinker (produced-export+import) in the corresponding country. Note that the annual national calculated emission values from produced clinker thus should be adjusted for exports and imports of cement clinker.

The annual CO<sub>2</sub> uptake in existing concrete structures mostly depends on the last few years of cement use; however, the historical use of cement may also play an important role. In order to calculate annual uptake, 100 year of historic cement clinker consumption should therefore be estimated, when possible (see Chapter 5.2 and 5.3 for more information on how to develop long historical time series for cement clinker use in a country). For countries with rather stable historical cement use, taking only the last few years or decades into account may, however, be sufficient; it would also require less time and resources to perform the calculations.

As presented in Chapter 5.3 above, the carbonation in cement products of lower quality (<15Pa) tend to go considerably faster than more robust structures. Lower quality products include cement mortar/render/plaster. The IVL Tier 1 simplified methodology should accommodate calculation of uptake in such products separately from products with slower carbonation. That means that the national statistics on consumed cement clinker need to be split into two groups: mortar/render/plaster and other cement products, respectively.

The text of Chapter 5.5.1 to 5.5.4 presumes the use of limestone as the CaO source for clinker production. If non-traditional pre-calcined raw materials are used as a CaO source besides limestone, the uptake cannot be directly related to the calcination emissions. See Chapter 2.2 for background and Chapter 5.5.5 for calculation of CO<sub>2</sub> uptake.

### 5.5.1.1 IVL Tier 1 method for annual uptake in primary use, End-of-Life and secondary use stages

Taking into account the method proposed for annual accounting of carbonation in the existing cement products for the last 100 years (see Chapter 5.2), where the square root effect of carbonation in the existing cement products is calculated, an IVL Tier 1 method for annual uptake in primary use, End-of-Life and secondary use stages is proposed below.

The method is based on alternative A (see Chapter 5.5.3), i.e. that carbonation in the primary use, end-of-life and secondary use stages can be estimated at 23% (20%+2%+1%) of the CO<sub>2</sub> emissions from calcination in the cement clinker used. For countries with elaborative procedures for handling concrete at end-of-life and for secondary use, the estimated uptake factors for end-of-life and secondary use stages may be conservative and thus result in underestimated annual CO<sub>2</sub> uptake. For such countries, it is advised that additional information is used to estimate uptake at end-of-life and for secondary use, or that countries move to a higher IVL Tier method.

For countries with high share of roof tiles/mortar/render/plaster (>10%), the IVL Tier 1 method allows for separate uptake calculations accordingly.

In the model, it is assumed that the carbonation starts the same year as the cement is produced/imported.

Generically, to be able to calculate the uptake a specific year  $x$  (one year), the cumulative uptake during  $t$  years is subtracted by the cumulative uptake the previous  $(t-1)$  years. Thus, the uptake during year  $x$  can be written as:

CO<sub>2</sub> uptake for a specific year  $x$  = CO<sub>2</sub> cumulative uptake ( $t$ ) – CO<sub>2</sub> cumulative uptake ( $t-1$ ).

Another way of describing this is that the uptake a specific year (x) is the sum of the yearly uptake contribution as a function of the calcination emissions and the square root of time dependency.

To calculate the IVL Tier 1 annual uptake (AU) in tonne in all three stages (primary use, End-of-Life and secondary use), year x, based on historical cement use, the following general equation can thus be used:

$$AU(\text{year } x) = \sum_{t=1}^{cp} \left( (CO_2 \text{ calc}_{x-cp+t} * UF) \left( (\sqrt{cp+1-t} - \sqrt{cp-t}) / \left( \sum_{t=1}^{cp} (\sqrt{cp+1-t} - \sqrt{cp-t}) \right) \right) \right)$$

Where,

$AU(\text{year } x)$  = Annual carbonation in cement products in year x in tonne from primary use, End-of-Life and secondary use.

$Cp$  = Total carbonation calculation period, number of years of service life until product EoL or reach of full carbonation (whichever is first); dependant on cement product (In IVL Tier 1, 100 years is assumed for all cement products except mortar/render/plaster, for which 3 years are assumed).

$t$  = each year of the carbonation calculation period (cp), starting the same year as of the CO<sub>2</sub> calcination emissions and is based on the cement use, i.e. t goes from 1 to cp.

$CO_2 \text{ calc}_{x-cp+t}$  = CO<sub>2</sub> emissions in tonne from calcination in the amount of cement used at year (x – cp + t). For example, to calculate uptake in 1990, annual CO<sub>2</sub> emissions from calcination in used cement from 1891-1990 need to be estimated.

$UF$  = Uptake Factor, as a share of CO<sub>2</sub> emissions from calcination. For countries with low share of mortar/render/plaster (<10%) of total cement use:  $UF=0.23$ . For countries with higher share of mortar/render/plaster (>10%) of total cement use:  $UF = 0.0023 (OC+10\%) + 0.0115(MRP - 10\%)$ , where MRP is the assumed share (%) of mortar/render/plaster (%) and OC is the assumed share (%) of other cement products. The maximum share of mortar/render/plaster is assumed to be 30%.

### **Assuming 100-year carbonation for all cement products**

If the national use mortar/render/plaster falls below 10% of total cement use, the uptake factor ( $UF$ ) is set to 0.23 and the total carbonation calculation period ( $cp$ ) is assumed to be 100 years, which gives the following simplified equation:

$$\text{Annual uptake (year } x) = \sum_{t=1}^{100} \left( (CO_2 \text{ calc}_{x-100+t} * 0.23) \left( (\sqrt{101-t} - \sqrt{100-t}) / (10) \right) \right)$$

### **Accounting for high share of fast-carbonating products**

In situations where mortar/render/plaster accounts for over 10% of the annual use of cement clinker, consideration need to be taken for the higher annual uptake. As these products carbonates significantly faster, the uptake is mainly dependant on the last few years. In the IVL Tier 1 method, we assume full carbonation for low-quality products in 3 years based on the k-factor values for ≤15 Pa concrete strength presented in EN 16757:2017, Annex BB.

To estimate the annual uptake, the annual CO<sub>2</sub> calcination emissions from cement clinker used is split into two groups: mortar/render/plaster (MRP) and other cement (OC) products, respectively. Uptake factors ( $UF_{OC}$  and  $UF_{MRP}$ ) need to be applied for each group, respectively:  $UF_{OC} = 0.0023$  and  $UF_{MRP} = 0.0115$ . National total uptake is then calculated as:

$$\text{Annual Uptake}_{total}(\text{year } x) = \text{Annual Uptake}_{OC}(\text{year } x) + \text{Annual Uptake}_{MRP}(\text{year } x)$$



Where,

$$Annual\ Uptake_{OC}(year\ x) = \sum_{t=1}^{100} \left( (CO2\ calc_{x-100+t} * (OC + 10\%) * UF_{OC}) \left( \frac{(\sqrt{101-t} - \sqrt{100-t})}{(10)} \right) \right)$$

$$Annual\ Uptake_{MRP}(year\ x) = \sum_{t=1}^3 \left( (CO2\ calc_{x-3+t} * (MRP - 10\%) * UF_{MRP}) \left( \frac{(\sqrt{4-t} - \sqrt{3-t})}{(\sqrt{3})} \right) \right)$$

Alternatively, to simplify the IVL Tier 1 calculations in situations with rather stable annual use of cement clinker and stable share of mortar/render/plaster of total cement use the last decades, one can assume a combined uptake factor (CUF), including uptake in mortar/render/plaster and other cement products: CUF = 0.0023 (OC+10%) + 0.0115(MRP – 10%). However, this may introduce higher uncertainty in the annually estimated uptake as the uptake in mortar/render/plaster will not correctly be allocated to the appropriate year.

$$Annual\ uptake\ (year\ x) = (CO2\ calc_x * CUF)$$

The table below shows precalculated combined uptake factors for four different levels of MRP that could be used to simplify the calculations even further.

Share of mortar/render/plaster (%)	Assumed share (%) mortar/render/plaster (MRP)	Share of other cement products (%)	Assumed share (%) of other cement products (OC)	MRP uptake factor contribution	OC uptake factor contribution	Combined Uptake Factor (CUF)
0-9	0	100-91	100	0.00	0.23	0.23
10-19	10	90-81	90	0.00	0.23	0.23
20-29	20	80-71	80	0.12	0.21	0.32
30-	30	-70	70	0.23	0.18	0.41

The following chapters explain the background and consideration that underlie the proposed model.

## 5.5.2 Introduction

CO<sub>2</sub> uptake takes place in cement-based concrete or mortar/render/plaster and not in the unhydrated cement powder, but there is of course a relation between the amount of cement used and the amount of concrete produced. This relationship can be used for the design of a simplified methodology for CO<sub>2</sub> uptake in concrete. It can be assumed that the CO<sub>2</sub> uptake one year in a given region or country is related to the cement consumption in the same area.

The process-related CO<sub>2</sub> emissions at cement production is almost solely coming from the calcination (clinker burning). These emissions are annually reported by many countries to UNFCCC, using one of the three IPCC methods (Tier 1, 2 or 3). Independent of which of the methods is used, and since

the uptake takes place in the hydrated clinker components, the annual CO<sub>2</sub> uptake can be estimated by multiplying the calcination emission by a factor < 1. This simple methodology (named IVL Tier 1 to be in line with the IPCC terminology) should, as well as the emission reporting, be possible to use for all cement production. For possible uptake in other constituents than clinker, see Chapter 5.4.8 on “Cement with additions.....” below. The magnitude of this factor is crucial to establish. Below, in the chapter on the use stage, a suggestion is presented.

The main constituent of cement is normally clinker, which is formed in the cement kiln. The CO<sub>2</sub> emissions used in these calculations are only CO<sub>2</sub> that is driven off from the raw material (e.g. limestone) in the cement kiln. This is referred to as calcination in this study. The CO<sub>2</sub> emission from the combustion in the cement kiln and other processes is not involved in the uptake calculations.

The theoretical maximum CO<sub>2</sub> uptake value is mainly the same as the CO<sub>2</sub> emissions from calcination of the raw material. This corresponds to a factor of 1.0. Such high uptake, also referred to as 100 % degree of carbonation, can eventually be found in very well hydrated concrete pieces with good access to CO<sub>2</sub> and moisture and after a considerable time. In reality, a practical maximum value of 75 % is reported in the European standard EN 16757 and in other literature references, for instance [11]. This value is valid for concrete, after use phase and followed by demolishing, crushing, and secondary use. It is accordingly a value that, for the bulk of concrete, takes a long time to achieve, so despite the long history of cement use, there are probably still only small amounts of concrete that has reached this status.

The practical maximum uptake value, 75 % of the emission, can only be achieved if the production of cement had been on the present level for a long time (meaning that the addition of concrete structures each year has been approximately the same and thus formed a concrete product stock that can take up CO<sub>2</sub> each year) and all of the structures or their demolished and crushed residue would carbonate. With an increasing amount of cement and concrete production, it is inevitable that the uptake, taking place in earlier production, will be lower than the emission from the present production. Thus, in many cases, it is important to account for historical cement clinker use when calculating annual uptake also with the IVL Tier 1 method.

### 5.5.3 The use stage of primary product

To be able to have knowledge of the annual uptake in the existing concrete products and crushed materials, one need to perform studies and calculations based on the use of concrete. This has been done in several countries and is reported in the reference list [2,3,20,5,4,13,12,6,7,8]. An overview can be found in Annex 2, Table 31. These studies are also the basis for the development of the Advanced methodology I and II (see Chapter 5.4). The methods used in different countries are all based on the well-accepted and documented carbonation rate model of square root of time dependency [11,19]. The inventories of existing concrete structures comprise different applications, exposure, and concrete quality. The age distribution of concrete in place is estimated by cement consumption statistics over time. This makes it possible to calculate a good estimate of the annual CO<sub>2</sub> uptake in the existing structures.

Seven such studies are compiled in Annex 2, Table 31, “Characterization of existing models...” representing Ireland, the Netherlands, Norway, Spain, Sweden, Switzerland, and “Global”. The annual CO<sub>2</sub> uptake, for these models, in the existing concrete structures has been found to be 16, 30, 24, 3, 27, 16, and 44 % of the corresponding calcination emissions the same year.

In the referred table and references, some values can include uptake also in end-of-life and secondary use, but these values are very small, compare Chapter 5.5.4, so the numbers are valid for, and here used, for the primary products only. Some numbers are also given as percentage of total production emissions instead of percentage of calcination emissions. Those numbers have been multiplied by 1.6 to get the uptake as percentage of calcination emissions given above.

The presented numbers on uptake in relation to calcination emissions can be used to estimate a general uptake number with the help of a statistical evaluation. Before that, some of the numbers need however explanations, comments or adjustments.

The comparably low value from the **Irish study** [5] (16 %) is said to be conservatively estimated.

The value from the **Netherlands** [20] is given in the table as 19 % of the production emissions, which multiplied with 1.6 gives 30 %. It is in the report assumed that the maximum CO<sub>2</sub> uptake of the slag is 0.14 kg CO<sub>2</sub>/kg slag, corresponding to  $0.14 \times 1\,440\,000 = 201\,600$  tonne. The maximum CO<sub>2</sub> uptake in slag will however, as in the clinker, not be reached. If we assume that the real uptake in the slag part is 25 kg CO<sub>2</sub>/tonne of slag (see Chapter 5.4.8 Cement with additions...) we get an uptake of  $0.025 \times 1\,440\,000 = 36\,000$  tonne. This leaves  $365\,000 - 36\,000 = 329\,000$  tonne to be taken up in the clinker, corresponding to  $329\,000 / 1\,318\,000 = 25\%$ . Therefore, the clinker uptake/clinker emission is reduced from 30 to 25 %.

No adjustments are done related to the **Norwegian report** [3].

The **Spanish value** [6,7,8] of uptake related to the calcination emission is very low, only 3 %. Some reasons can be identified for the low value compared to the other studies. It is declared that the study is deliberately held on a very conservative level. The report is providing measured uptake values for laboratory samples and drilled out field samples. Uptake is estimated for a service life of 50 years for buildings and 100 years for infrastructures. The reported degree of carbonation is generally small, which for the laboratory specimens might be explained by the short time and dry testing conditions. Moreover, it is anticipated that the uptake in all interior surfaces and surfaces in contact with other materials, as well as buried concrete, is zero. The specific surface area (m<sup>2</sup>/m<sup>3</sup>) for the structures is also low, about 2 m<sup>2</sup>/m<sup>3</sup> concrete. The large deviation from the other cement application values makes it difficult to include it in the statistical calculations below.

In a paper by C. Andrade : “Evaluation of the Degree of Carbonation in three Environments”[9], the earlier low values of degree of carbonation have been revised and updated, resulting in an uptake value increase to 10.8 – 11.2 % of the calcination emissions. However, the assumption of zero uptake in interior surfaces and buried surfaces remain, as well as a comparably low specific surface area for the interior concrete. The motive for zero uptake in interior surfaces is that these surfaces very often are coated by for instance paint or wallpaper.

From experience and established in literature, for instance [2,3,11,13] it has been shown that CO<sub>2</sub> uptake takes place, even if with reduced speed, also in surfaces with some kind of coating and also under ground. See also European standard CEN/EN 16757, Annex BB.

For the purpose of this report a further recalculation of the Spanish value has accordingly been done, bringing it in line with the common view of uptake in coated surfaces and surfaces underground (“normalization”).

From the Spanish report [7], Table 31 it follows that 60 % of the concrete for building structures has been classified as “not exposed”. 21 % of it is located in foundations.

We now assume that the remaining 39 % “not exposed” are parts with some kind of cover, and, based on EN 16757, table BB1, that the uptake in such surfaces is reduced with the factor 0.7 (with cover/without cover). We also assume that the 21 % are under ground and that the uptake there is reduced with the factor 0.25 (in ground/½(exposed+sheltered)).

The buildings 60 % “not exposed”, can now be calculated to correspond to

$$0.7 \times 39 + 0.25 \times 21 = 32.6 \text{ \% of exposed.}$$

Further the specific surface for these, so far not included, parts is anticipated to be at least 6 m<sup>2</sup>/m<sup>3</sup> compared to 3 for the included building surfaces. (The Fpr CEN/TR 17310:2018 presents 8 m<sup>2</sup>/m<sup>3</sup> as a typical value for buildings, including interior parts.) The value is then increased to  $(6/3) \times 32.6 = 65 \text{ \%}$ .

This gives us for buildings  $1.65 \times 10.8 = 17.8 \text{ \%}$ . (10.8 % being the value according to C. Andrade’s paper [9].)

From [7], Table 31 it follows that 44 % of the concrete for civil works has been classified as “not exposed”. It is assumed that this concrete is under ground and, as above, that it corresponds to  $0.25 \times 44 = 11 \text{ \%}$  of the above ground value.

This gives for civil works  $1.11 \times 11.2 = 12.4 \text{ \%}$ . (11.2 being the value according to C. Andrade’s paper. [9])

The relation in Spain between concrete used for buildings and for civil works is about 47/53. (Cement consumption statistics from Cembureau 2016.)

We now get for all concrete structures  $0.47 \times 17.8 + 0.53 \times 12.4 = 14.9 \text{ \%}$

The Spanish CO<sub>2</sub> uptake value used for the statistical calculation below; is accordingly 15 % of the calcination emissions.

No adjustments are done related to the **Swedish report** [2].

In the **Swiss report** [13], the degree of carbonation is set to 75 % throughout, but is later in another paper [12] changed to 50 %. An average uptake of 10 % of the total emissions, for 50 years is presented in the report. For the calcination emissions, the figure can be estimated to be  $10 \times (1/0.63) = 16 \text{ \%}$ . For 100 years, the figure can be estimated to be  $16 \times \sqrt{(100/50)} = 23 \text{ \%}$ . With degree of carbonation being 50 % instead of 75 %, we get  $23 \times (50/75) = 15 \text{ \%}$ . (According to the Annex BB of the EN 16757, the degree of carbonation varies between 40 % for indoor structures to 85 % for outdoor structures not sheltered from rain.)

The **global value** [4] of 44 % should be adjusted due to the very large amount of mortar/render/plaster included in the study (see also Chapter 5.5.3.1). The mortar/render/plaster contribution to the CO<sub>2</sub> uptake is about 70 % of the global study value 44 %, though the amount of cement used for this application is about 30 %. The concrete and mortar/render/plaster uptake figures can be calculated as follows.

Assume that the uptake factor for concrete is  $c$  and the factor for mortar/render/plaster is  $m$ .

The factor for concrete and mortar/render/plaster together is 0.44. Then

$$70c + 30m = 100 \times 0.44$$

$c/m = 30 \times 30 / 70 \times 70 = 0.18$  (70 % of concrete accounts for 30 % of the uptake and vice versa for mortar/render/plaster.)

$$70 \times 0.18m + 30m = 44$$

$$m = 44 / 42.6 = 1.03$$

$$c = 0.18 \times 1.03 = 0.19$$

The uptake factor for concrete is thus 0.19, (19 %).

(It should be noted that this calculation, with reduction of the mortar/render/plaster portion, shows that the high global value of 44 % is reduced to a more typical value of 19 %, which strengthens the credibility of the global study.)

After these comments, the series of numbers of CO<sub>2</sub> uptake related to calcination emissions to be used for the statistical evaluation are: 16, 25, 24, 27, 15, 15 and 19 %<sup>5</sup>.

The statistical population of all countries' figures of CO<sub>2</sub> uptake in cement-based products, related to the calcination emissions, could probably be considered approximately normally distributed. If we perform a very simple statistical analysis of the results, assuming normal distribution, we end up with a mean value of 20 % and a standard deviation of 5.1 %. The value 15 % accordingly corresponds to (Mean - 1 × St. dev.) and is a value with some safety margin.

The 95 % confidence interval based on the seven numbers equal  $1.96 \times (5.1/\sqrt{7}) = 3.8$  %. The mean value could then be presented as 20 % +/- 3.8 %.

It should be noted that the statistical basis is only six country values and one global value. The base for the seven single numbers varies also for instance with statistical accuracy and with different cement types. The studies cover however a large number of structures and products.

Even if the seven studies are independent of each other, they cannot be considered as randomly selected or a statistically representative sample of an average country's annual concrete CO<sub>2</sub> uptake. The true mean value could thus deviate from 20 % and the 95 % confidence interval is thus likely larger than 3.8 %.

With a mean cement consumption as basis, instead of a single year value, the accuracy of the relative uptake values presented for the different countries should be more accurate. Below, the mean cement consumption during the years 2011-2016, Table 30, is used as basis for the calculation of the relative CO<sub>2</sub> uptake value for five countries.

---

<sup>5</sup> Since the second version of this report, the UK has published a study [24] based on a Tier 2 model, in which the estimated uptake of CO<sub>2</sub> from concrete in primary product use 1990-2020 ranges between 14% and 20% of the annual cement calcination emissions (on a consumption basis).

**Table 30 Yearly cement consumption in ktonne <sup>6</sup>.**

Country	2011	2012	2013	2014	2015	2016	Average (μ)	Standard deviation (σ)	Coefficient of variation (σ/μ)
Ireland	1 310	1 130	1 064	1 195	1 720	1 820	1 373	319	0.23
Netherlands	5 596	5 079	3 991	4 100	4 040	4 110	4 486	681	0.15
Norway	1 874	1 943	1 993	1 967	1 960	2 060	1 966	61	0.03
Sweden	2 440	2 340	2 235	2 200	2 270	2 360	2 308	89	0.04
Switzerland	5 299	5 014	5 274	5 370	4 900	5 000	5 143	195	0.04

The so far presented numbers (based on the single year values) for the five first countries are 16, 25, 24, 27 and 15 %.

The single year values used for the calculation of these numbers are the following:

Ireland: 2000 ktonne  
 Netherlands 4040 ktonne  
 Norway: 1550 ktonne  
 Sweden: 2440 ktonne  
 Switzerland: 4553 ktonne

(The actual year lies sometimes before 2011 or has been modified in the referred country report. The single year value used for Spain is not known so no calculation has been made.)

If we chose to use the six years mean value instead, we get the following corrected numbers:

Ireland  $(2000/1373) \times 16 = 23 \%$   
 Netherlands  $(4040/4486) \times 25 = 23 \%$   
 Norway  $(1550/1966) \times 24 = 19 \%$   
 Sweden  $(2440/2306) \times 27 = 28 \%$   
 Switzerland  $(4553/5142) \times 15 = 13 \%$

With these new numbers, we get, including the Spanish value 15 and the global value 19 % unchanged:

Mean value: 20.0 %  
 St. dev.: 5.13 %

These values are very similar to the ones we got with the single year basis.

Two alternative calculations, A and B, for the CO<sub>2</sub> uptake in the primary use stage are given. The reason for giving two values is to give options how to handle the variation span of the calculated

---

<sup>6</sup> Data from VDZ (Verein Deutscher Zementwerke e.V.). VDZ is the economic, technical and scientific association for the German cement industry.

figures. From Chapter 5.5.3 it follows that one can present a calculated mean value (A) or a low (=Mean - St. dev.) value (B). The IPCC recommendation is to neither overestimate, nor underestimate in the calculations, which should indicate alternative A. The IVL Tier 1 methods are associated with relatively large uncertainties in the calculated uptake figures. To reduce uncertainties, higher tier-levels methods should be used.

#### **Alternative A:**

The total uptake in the primary use stage can be estimated as  $0.20 \times$  (the reported CO<sub>2</sub> emissions from calcination of consumed cement clinker).

If the mortar/render/plaster applications, in total, amount to more than 10 % but less than 30 % of the cement consumption, the uptake factor in the primary use stage can be estimated at  $0.0020(OC + 10\%) + 0.0115(MRP - 10\%)$ , where MRP is the mortar/render/plaster percentage of the clinker use and OC is the percentage of other cement products. If MRP is below 10 % use MRP=10% and if MRP is above 30 % use MRP=30%.

#### **Alternative B:**

The total uptake in the primary use stage can be estimated as  $0.15 \times$  (the reported CO<sub>2</sub> emissions from calcination of consumed cement clinker).

If the mortar/render/plaster applications, in total, amount to more than 10 % but less than 30 % of the cement clinker consumption, the uptake factor in the use stage can be estimated at  $0.0015(OC + 10\%) + 0.01(MRP - 10\%)$ , where MRP is the mortar/render/plaster percentage of the clinker use and OC is the percentage of other cement products. If MRP is below 10 % use MRP=10% and if MRP is above 30 % use MRP=30%.

**The mean value is, as mentioned above, 20 %, (IVL Tier 1A).**

**In order to estimate the annual uptake with a conservative approach, it is accordingly suggested that the annual emissions could be multiplied with the factor 0.15 to handle the variation span in the Simplified methodology (IVL Tier 1B).**

It is likely to believe that the Simplified methodology will be used in most countries, at least in the beginning of the calculation of CO<sub>2</sub> uptake in concrete and other cement containing products. However, due to the simplifications of the calculations used in the method, the uncertainty will be relatively high, and the accuracy of the national calculations can be poor. The uptake factor can, in reality, vary between different countries, which a general uptake factor cannot account for. However, on a global scale, the average uptake value will be reflected by the general uptake factor.

Technical factors, such the use of mortar/render/plaster, can have a significant impact on the uptake, thus an addition to the IVL Tier 1 method is developed below.

### **5.5.3.1 Influence of high use of mortar/render/plaster (from the global study)**

The following indicates a method to consider a high mortar/render/plaster use in the cement applications. It is based on the global study [4] of the "Characterization table in annex 2, Table 31".

The mortar/render/plaster contribution to the CO<sub>2</sub> uptake is about 70 % of the global study value of 44 % carbonation, though the amount of cement used for this application is about 30 %.

The concrete and mortar/render/plaster uptake figures can be calculated as follows:

Assume that the uptake factor for concrete is  $c$  and the uptake factor for mortar/render/plaster is  $m$ . The factor for concrete and mortar/render/plaster together is 0.44. Then

$$70c + 30m = 100 \times 0.44$$

$c/m = 30 \times 30 / 70 \times 70 = 0.18$  (70 % of concrete accounts for 30 % of the uptake and vice versa for mortar/render/plaster.)

$$70 \times 0.18m + 30m = 44$$

$$m = 44 / 42.6 = 1.03$$

$$c = 0.18 \times 1.03 = 0.19$$

The uptake factor for concrete is thus 0.19, which seems to be a reasonable value.

The uptake factor for mortar/render/plaster is very high, 1.0. It means that all cement used for mortar/render/plaster applications is totally carbonated already after one or a few years. This result is also apparent from the global report [4] as a result of thin structures ( $\approx 20$  mm), high rate of carbonation ( $k = 19.6$ ) and high degree of carbonation (average 92 %). This can be explained by a high use of mortar/render/plaster.

The factors 0.15 or 0.20 are suggested above to be valid for more real concrete applications, say with a render or plaster use of less than 10 %. If the render or plaster use is larger than 10 %, an adjustment factor could possibly be used. With the render/plaster share being 30 %, the uptake factor is 0.44. If one then assumes a linear increase of the uptake factor between a render/plaster content of 10 % and 30 %, we obtain:

The total uptake in the primary use stage can be estimated as  $0.20 \times$  (the reported CO<sub>2</sub> emissions from calcination of consumed cement clinker).



**Alternative A (IVL Tier 1A)**

With 0 – 10 % of cement use in mortar/render/plaster applications, the uptake factor will be 0.20.

With 10 – 30 % of cement clinker use in render or plaster applications, the uptake factor will be:  $0.0020(OC+10\%) + 0.0115(MRP - 10\%)$ , where MRP is the mortar/render/plaster percentage of the clinker use and OC is the percentage of other cement products (100%-MRP). If MRP is below 10 % use MRP=10% and if MRP is above 30 % use MRP=30%.

**Alternative B (IVL Tier 1B)**

With 0 – 10 % of cement clinker use in render or plaster applications, the uptake factor will be 0.15.

With 10 – 30 % of cement clinker use in render or plaster applications, the uptake factor will be:  $0.0015(OC+10\%) + 0.01(MRP - 10\%)$ , where MRP is the mortar/render/plaster percentage of the clinker use and OC is the percentage of other cement products (100%-MRP). If MRP is below 10 % use MRP=10% and if MRP is above 30 % use MRP=30%.

## 5.5.4 End-of-life (EoL) stage and secondary use

In addition to the CO<sub>2</sub> uptake over the use stage of structures, there is uptake in the end-of-life stage and the secondary use, normally as crushed material. Detailed information on the amount of this material and its uptake is rare, so it is today difficult to give a reliable estimate. The percent of concrete recycling, given in some countries is unfortunately not sufficient, since it is mainly the service life at demolition, the processing of the demolished material and the applications for the crushed concrete that determines the actual uptake.

### 5.5.4.1 End-of-life stage (demolishing, crushing and storage)

The EN 16757, Annex BB [16] indicates a conservative value of a CO<sub>2</sub> uptake in the end-of-life stage (demolishing, crushing, and storage) of  $5 \text{ kg CO}_2/\text{m}^3$  of concrete with present waste handling systems. With an average cement content of  $330 \text{ kg}/\text{m}^3$  concrete, this corresponds to approximately  $5/0.330 = 15 \text{ kg CO}_2/\text{tonne}$  of cement or  $15/490 = 3 \%$  of a Portland cement calcination emission. The figure  $5 \text{ kg CO}_2/\text{m}^3$  of concrete indicates a very small uptake in this stage. The potential to increase this value by applying a more advanced waste processing systems is however very large.

The **Swedish study** [2] reports that about 1.5 million tonne ( $625\,000 \text{ m}^3$ ) of concrete is annually demolished. The annual uptake in the end-of-life stage and secondary use is presently estimated to be only 12 000 tonne and of that, about 4000 tonne of the 12 000 tonne of uptake after the use stage takes place in the end-of-life stage. This corresponds to  $4\,000\,000/625\,000 = 6.4 \text{ kg CO}_2/\text{m}^3$  of concrete or  $6.4/0.33 = 19 \text{ kg CO}_2/\text{tonne}$  cement, or  $19/490 = 4 \%$  of a Portland cement calcination emission.

Since the annual amount of concrete taken out of the service life is rather small compared to the annual production,  $625\,000/7\,000\,000 \text{ m}^3 = 9 \%$ , the uptake is small in relation to the annual calcination emissions, only about 0.4 %,  $(0.09 \times 0.04 \times 100) \%$ .

The “**global**” study [4] value 44 % includes uptake in the end-of-life stage. The average exposure time is 0.4 years. The relative uptake in this stage is reported to be around 8 % ( $1.4/(16.1+1.4)$ ) in concrete and around 2 % in mortar/render/plaster.

With about 70 % concrete and 30 % mortar/render/plaster we end up with a mean figure of about

$$0.70 \times 0.08 + 0.30 \times 0.02 = 0.06$$

Thus, about 6 % of the uptake takes place in the end-of-life stage. This corresponds to a factor  $0.06 \times 0.44 = 0.026$  or 2.6 % of the annual calcination emissions. The total calcination emission being 0.55 Gt C, corresponding to  $(44/12) \times 0.55 = 2.02$  Gt CO<sub>2</sub>. The 2.6 % means an uptake in the end-of-life stage of  $0.026 \times 2.02 = 0.0525$  Gt or 52.5 million tonne of CO<sub>2</sub>. The annual amount of concrete entering the end-of-life stage is not found in the report. The uptake can therefore not be presented as kg CO<sub>2</sub>/m<sup>3</sup> of concrete.

The **Norwegian study** [3] reports that the “concrete demolition rate is 10 % of the consumed concrete volume” and that 90 % of the demolished concrete “recovery rate” is available for carbonation. No figures are specified for the end-of-life stage. For a 100-years “recovery phase”, a scenario is however presented, see Secondary use.

In **the Netherlands** [20], the amount of annual demolished concrete as a percentage of annual production is high, 5.1 million m<sup>3</sup> out of 14 million m<sup>3</sup>, corresponding to 36 %. The Dutch study reports an uptake in the end-of-life stage of 83 000 tonne per year. The calcination emission is 1 960 000 ton, which means that the uptake in the end-of-life stage is reported to be  $83\,000/1\,960\,000 = 4$  % of the calcination emissions. Slag cement is here a considerable part of the cement consumption. The uptake per m<sup>3</sup> of demolished concrete is  $83\,000\,000/5\,100\,000 = 16$  kg CO<sub>2</sub>/m<sup>3</sup> concrete.

Measurements of CO<sub>2</sub> uptake in crushed concrete from demolition sites and recycling plants are reported in (Kikuchi T and Kuroda Y, 2011) [10]. The presented figure of the CO<sub>2</sub> uptake in a couple of months is 11 kg per tonne of crushed concrete, corresponding to about 25 kg CO<sub>2</sub>/m<sup>3</sup> of concrete, or to about  $25/0.330 = 76$  kg CO<sub>2</sub>/tonne cement, or to  $76/490 = 15$  % of the calcination emissions for the cement in the crushed concrete, (Portland cement anticipated). The relation of the uptake at the end-of-life stage, to the annual total calcination emission, can be calculated if the annual recycled amount and the production can be found. The annual amount of CO<sub>2</sub> uptake by “recycled crusher run” is estimated at 0.37 million tonne. The annual produced amount of concrete is 500 million tonne, or about 200 million m<sup>3</sup>. The average cement content is assumed to be 330 kg/m<sup>3</sup>, and the calcination emission 0.480 kg CO<sub>2</sub> per kg cement. The emission per m<sup>3</sup> concrete will be  $330 \times 0.480 = 158$  kg CO<sub>2</sub>/m<sup>3</sup> concrete. The relative uptake is accordingly:

$$370\,000/200\,000\,000 \times 0.158 = 0.012 \text{ or } \underline{1.2 \text{ \% of the total calcination emissions.}}$$

Considering that the concrete that is taken out of service annually is normally only a minor part of the annual production, it means that the uptake in this stage compared to the emissions is normally small. This means also that any default factor value of the calcination emissions in the Simplified methodology need to be small, (e.g. range of 0.4 – 4 %). If there, however, exists knowledge of the annual amount of concrete taken out of service (often referred to as recycled concrete), the uptake in this concrete during the end-of-life stage can be estimated to be in the range of 5 - 25 kg CO<sub>2</sub>/m<sup>3</sup> of concrete.

For the Simplified methodology, it therefore seems reasonable to suggest two principal ways to report an estimated uptake value in the end-of-life stage:

**If the annual amount of concrete in the end-of-life stage is known (m<sup>3</sup> per year), the uptake can be calculated as 10 kg CO<sub>2</sub>/m<sup>3</sup> of concrete.**

**If the annual amount of concrete in the end-of-life stage is not known, the uptake can be calculated as 2 % of the annual calcination emissions, (factor 0.02). This also includes an anticipated minor increase of concrete to end-of-life the coming years. The choice of uptake values in EoL includes both the potential CO<sub>2</sub> uptake in the material and the amount of demolished concrete today. Much of the concrete produced since year 1900 may still be in use, which is why relatively little concrete is demolished today. This can of course change over time and vary between different countries.**

Potential uptake in the end-of-life stage (demolition, crushing, and stockpiling) is very large if adequate measures are taken. The measures are storage of the crushed material in fractions and sheltered from rain in order to enhance air circulation in the piles, [17] and draft FprCEN/TR 17310, Carbonation and CO<sub>2</sub> uptake in concrete. See also the Advanced methodology. For countries with well-documented and improved end-of-life handling procedures, the suggested factors above are thus too conservative. In such cases, a higher IVL tier method is recommended. Since the second edition of this report, the UK has published a study [24] based on a Tier 2 model, in which the estimated uptake of CO<sub>2</sub> in concrete in end-of-life and secondary product use 1990-2020 ranges between 9% and 16% of the annual cement calcination emissions (on a consumption basis).

#### 5.5.4.2 Secondary use

The uptake in secondary use, mainly in various applications for crushed concrete, is probably of great importance but very few reports present reliable uptake in this case. The secondary use phase reminds a lot of the primary use phase. By crushing or other processing, new concrete surfaces for carbonation are exposed while old surfaces and volumes can continue to carbonate. Thus, similar methods as for primary concrete products can be utilized.

The **Swedish study** [2] estimates that about 8000 of the 12 000 tonne of the uptake after the use stage takes place during the “use of the mixed crushed concrete fractions”, that is as secondary use. This corresponds to  $8\,000\,000/625\,000 = 12.8\text{ kg CO}_2/\text{m}^3$  of concrete, or  $12.8/0.33 = 39\text{ kg CO}_2/\text{tonne cement}$ , or  $(39/490)*100 = 8\%$  of a Portland cement calcination emission. Since 1.5 million tonne (625 000 m<sup>3</sup>) of concrete is recycled each year and the production is about 7 000 000 m<sup>3</sup>, the relative recycling rate is 9 %. This means that the annual uptake in the recycled concrete is less than 1 % of the annual calcination emissions, ( $0.09 \times 0.08 \times 100 = 0.72\%$ ).

The **Norwegian study** [3] assumes a 100-years “recovery stage”. The scenario is an anticipated crushed concrete particle size distribution and 10 % exposed above ground and 90 % below ground. The annual uptake is estimated to be 25 000 tonne, corresponding to  $25\,000/795\,000 = 3\%$  of the annual calcination emissions. Counted as uptake related to the recovered material (1 million tonne or 400 000 m<sup>3</sup>) the figure is  $25\,000\,000/400\,000 = 62\text{ kg CO}_2/\text{m}^3$  concrete. This figure is actually the annual uptake in “recovered concrete” for 100 years, or the annual uptake 2011, assuming 100 years of 10 % recovery rate each year.

The **Dutch study** [20] doesn't present any values for the secondary use.

The **global study** [4] claims that only 0.1 % of the initial emission is absorbed during the disposal or reuse of the concrete waste. This corresponds to about  $0.001 \times 0.49 \times 330 = 0.16 \text{ kg CO}_2/\text{m}^3$  of concrete. It is uncertain however if “reuse of concrete waste” is the same as secondary use, so this very low value is, until more information is available, not taken into account.

**To summarize:** As in the “end-of-life stage”, only a minor amount of the annually produced concrete is presently normally taken out of service and being recycled. The uptake in the secondary use applications is for this reason small compared to the emissions of the produced concrete and cement.

The default value in the Simplified methodology (without any other data than calcination emissions) must therefore be modest. Proposed is 0.01 or 1 % of the calcination emissions.

For the Simplified methodology, it therefore seems reasonable to suggest two principal ways to report an estimated uptake value in the secondary use:

**If the annual amount of concrete entering the secondary use is known (m<sup>3</sup> per year), the uptake can be calculated as 10 kg CO<sub>2</sub>/m<sup>3</sup> of concrete. This value is valid for unbound applications of crushed material.**

**If the annual amount of concrete entering the secondary use is not known, the uptake can be calculated as 1 % of the annual calcination emissions, (factor 0.01).**

For countries with well-documented processes and producers for secondary use practices, the suggested factors above are thus too conservative. In such cases, a higher IVL tier method is recommended. Since the second version of this report, the UK has published a study [24] based on a Tier 2 model, in which the estimated uptake of CO<sub>2</sub> in concrete in end-of-life and secondary product use 1990-2020 ranges between 9% and 16% of the annual cement calcination emissions (on a consumption basis).

## 5.5.5 CO<sub>2</sub> uptake with non-traditional raw materials as CaO source beside limestone

Traditionally, calcium carbonate, CaCO<sub>3</sub>, has been used as the main calcium oxide source for clinker production. The CO<sub>2</sub> released during limestone calcination can be mineralized into calcium carbonate by the carbonation reaction and hence, the CO<sub>2</sub> emissions from raw materials (also called process or calcination emissions) can be equated with the maximum uptake of CO<sub>2</sub>.

With the decarbonization efforts of cement industry, it is expected that the fraction of pre-calcined calcium oxide sources for clinker production will increase. Such sources comprise e.g. of slags where CaO is bound in a pre-calcined glass, fines from concrete recycling where CaO is bound in cement hydrates, calcium hydroxide by-products, paper sludge incineration ash etc. Such materials do not release CO<sub>2</sub> upon heating, but still provide carbonatable CaO to the clinker, cement and concrete, respectively. As the CO<sub>2</sub> uptake is linked to the calcination CO<sub>2</sub> emissions in the Simplified methodology, these alternative pre-calcined raw materials would lead to underestimating the actual CO<sub>2</sub> uptake. This problem can be overcome by using the carbonation potential based on the bulk chemical composition.

Instead of using the calcination emission as maximum theoretical CO<sub>2</sub> uptake, one can use a calculation of the maximum theoretical CO<sub>2</sub> uptake according to the same principle as in IVL Tier 2, here called  $U_{\text{tcc}}$ .

$U_{\text{tcc}}$  is presented in Chapter 5.4.1.1 and 5.4.6 as being  $\approx 0.49$  kg CO<sub>2</sub>/kg cement (CEM I), or  $\approx 0.52$  kg CO<sub>2</sub>/kg clinker, but can be individually calculated with the following formula, which can be found for instance in the EN 16757, Annex BB.

$$U_{\text{tcc}} = (M_{\text{CO}_2}/M_{\text{CaO}}) \times \text{CaO} = 0.785 \times \text{CaO}$$

where

CaO is the part of reactive CaO in the binder.

$M_{\text{CO}_2}$  is the molar mass of CO<sub>2</sub> = 44 g/mol

$M_{\text{CaO}}$  is the molar mass of CaO = 56 g/mol

With limestone as raw material, a typical value for reactive CaO part is about 65 % by weight of clinker. The  $U_{\text{tcc}}$  then becomes  $0.785 \times 0.65 = 0.51$  kg CO<sub>2</sub>/kg clinker, which value is the same as the calcination emission. This is an approximative figure and if also CO<sub>2</sub> uptake in other compounds such as MgO will be taken into account, the uptake figure has to be increased to, for example, 0.52-0.54 kg CO<sub>2</sub>/kg clinker. The calcination/carbonation figure is specific for the clinker/cement used.

With non-traditional pre-calcined CaO sources as raw material besides clinker, the same formula can be used, but with the actual reactive CaO content of the clinker.

This value of  $U_{\text{tcc}} = 0.785 \times \text{CaO}$ , being the theoretical maximum of CO<sub>2</sub> uptake, can be used in all calculations according to Tier 1, instead of calcination emission.

## 6 Discussion and conclusions

Climate aspects are now regarded as one of the most important environmental issues both globally and nationally. Yearly statistics on emissions of greenhouse gases (e.g. CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) have been collected in many countries during many years and the emissions have then been compiled at a global level. Emissions of greenhouse gases have an impact on a global level. Thus, where an emission occurs is therefore of secondary importance. From the outset there was a clear focus on CO<sub>2</sub> from fossil fuel combustion. These emissions remain a very important contributing factor to the greenhouse effect, but recent research has shown that the cause of the greenhouse effect is considerably more complex, and several sources and sinks can contribute to the greenhouse effect. For example, CO<sub>2</sub> from combustion of biogenic fuels is not considered to contribute to the greenhouse effect when the growing biomass is considered to take up a corresponding amount of CO<sub>2</sub>, but this is only applicable if a replanting occurs. In the case of e.g. deforestation, in which no biomass regrowth occurs, CO<sub>2</sub> emissions from combustion of such biomass can be considered equivalent to CO<sub>2</sub> from fossil fuels, at least as long as the deforestation exists.

The insight into the complexity of climate and climatic effects has resulted in calculation methods for sources and sinks of climate gases that have been developed and broadened so that they now contain several different types of greenhouse gas calculations. This research study includes such a widening of the climate gas calculations by taking into account the uptake of CO<sub>2</sub> in concrete through carbonation. Carbonation is a process that has been known for a long time in the concrete chemistry but now has a new scope for climate gas calculations. Since concrete is not chemically stable, the concrete reacts with CO<sub>2</sub> in air under reformation of carbonates in the concrete. The carbonated concrete phases are chemically stable so there is no risk that the CO<sub>2</sub> that has been taken up will return to the atmosphere. This can only happen if the concrete is heated to a temperature where calcination can occur, i.e. about > 850 °C. Uptake of CO<sub>2</sub> in concrete through carbonation may be a significant global CO<sub>2</sub> sink and it is important for the climate change community that reliable carbonation estimations are available. This was noted by the Working Group I of the IPCC 6<sup>th</sup> Assessment Report [23].

Greenhouse gas calculations can be made within the framework of the IPCC at different levels of method complexity (Tier 1, Tier 2, Tier 3), presented in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. However, no methodology on carbonation in concrete is presented in the IPCC Guidelines. CO<sub>2</sub> emissions are often relatively easy to calculate, and control measurements can usually be made, even though the number of measurements that would have to be made can complicate the practical implementation. Simple linear calculations can often be used, using different standard emission factors. As regards to the estimations of national annual uptake of CO<sub>2</sub> through carbonation, the results of the present study show significant challenges. The uptake in a concrete surface cannot be directly measured on site but must be calculated based on laboratory and field measurements from previous research. Instead, calculation of a country's annual uptake of carbon dioxide by carbonation of concrete can be done by estimating the uptake in concrete surfaces on the concrete products in the country. However, the uptake is influenced by various factors such as weather (rain and moisture), surface coatings, surfaces under water and soil, and the quality of concrete. Such factors can vary significantly between regions and countries, which increases the difficulty of developing simplified methods that could be applied as an IPCC Tier 1 approach. Experience from previous estimates in the field of research shows that advanced calculation methods are to be preferred to make accurate calculations of annual uptake in a country. Another element

that contributes to the complexity is that a country's annual uptake in concrete structures depends on the historical use of cement clinker. Information on cement clinker use, up to 100 years ago, may thus be needed to accurately calculate today's annual uptake.

In this study, the methodological foundation for accurate estimations of uptake in concrete is presented in an IVL Tier 3 method that would require advanced modelling and vast knowledge on national concrete circumstances, which may be both resource and time consuming. Thus, in order for such calculations to be implemented in many countries with high quality, while being cost effective, common global computer models should be developed. These models can then be used for national calculations after a local adaptation to national inputs.

Here, an attempt has also been made to develop simplified calculation methods (IVL Tier 1 and IVL Tier 2) that could be used on a national and global scale, and as input to future methodological update of the IPCC Guidelines and the IPCC emission factor database. They generally generate less accurate uptake results compared to the IVL Tier 3, but instead requires significantly less resources to calculate. As more and more laboratory and field measurements are being developed, and countries start to calculate uptake in concrete products using advanced modelling, the suggested methods in this study could be updated to better reflect the national and global need for simplified calculations.

# References

1. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3: Industrial Processes and Product Use, Chapter 2 Mineral industry emissions.
2. Andersson R., Fridh K., Stripple H. and Häglund M., Calculating CO<sub>2</sub> Uptake for Existing Concrete Structures during and after Service Life, *Environmental Science & Technology*, 2013, 47 (20), pp 11625–11633.
3. Engelsen C.J., Justnes H., CO<sub>2</sub>-Binding by Concrete Structures during Life Cycle., Conference paper: 2nd International Congress on Durability of Concrete, 2<sup>nd</sup> ICDC, at New Delhi, India Volume: 1, December 2014.
4. Fengming Xi et al., Substantial global carbon uptake by cement carbonation, *Nature Geoscience* volume 9, pages 880–883 (2016).
5. Fitzpatrick D., Richardson M.G., Nolan E., Sequestration of Carbon Dioxide by Concrete Infrastructure: A Preliminary investigation in Ireland, 2015.
6. Galán I. et al., Estudio del efecto sumidero de CO<sub>2</sub> de los materiales de base cemento, *Cemento Hormigón*, ISSN 0008-8919, N<sup>o</sup>. 939, 2010, págs. 70-83. (in Spanish)
7. Galán I., Andrade C., Mora P., Sanjuan M.A., Lopez-Agtti J.C., Prieto M., Summary of the Study of the CO<sub>2</sub> Sink Effect of Cement Based Materials, English translation and summary of the Spanish report “Estudio del Efecto Sumidero de CO<sub>2</sub> de los Materiales de Base Cemento”, Spain, 2009.
8. Galán, I., Andrade, C., Mora, P. & Sanjuan, M. A. Sequestration of CO<sub>2</sub> by concrete carbonation. *Environ. Sci. Technol.* 44 (8), pp 3181–3186 (2010). DOI: 10.1021/es903581d.
9. Andrade C., Evaluation of the degree of carbonation of concretes in three environments, *Construction and Building Materials*, Volume 230, 10 January 2020, 116804.
10. Kikuchi T, Kuroda Y. Carbon dioxide uptake in demolished crushed concrete. *Journal of Advanced Concrete Technology* 9: 115-124 (2011).
11. Lagerblad Björn, Carbon dioxide uptake during concrete life cycle – State of the art, Swedish Cement and Concrete Research Institute (CBI), CBI Report 2:2005 ISBN 91-976070-0-2, ISSN 0346-8240 (2005).
12. Leemann A., Hunkeler F., Widmer H., Calculation of CO<sub>2</sub> binding during the service life of concrete., *cemsuisse*, March 2018.
13. Nygaard PV, Leemann A (2012) Carbon dioxide uptake of reinforced concrete structures due to carbonation. EMPA, Cemsuisse Project 201106.
14. Rogers P et al, “High Quality Reclaimed Concrete Aggregates for New Concrete”, SBUF (The Development Fund of the Swedish Construction Industry). ID:12771, (2016).
15. Silva, A., Neves, R. and de Brito, J., Statistical modelling of carbonation in reinforced concrete. *Cement Concr. Compos.* 50, 73–81 (2014).
16. Standard EN 16757:2017 and EN 16757:2022 Sustainability of construction works. Environmental product declarations. Product Category Rules for concrete and concrete elements.
17. Stripple Håkan, Greenhouse gas strategies for cement containing products. Part of the research project, CO<sub>2</sub> cycle in cement and concrete. IVL report B 2024, (2013).
18. Taylor H.F.W., *Cement Chemistry*, Academic Press Limited, London, (1990). 2<sup>nd</sup> Edition from Thomas Telford Publishing, 1997.
19. Tuutti, K., Corrosion of steel in concrete. CBI research 4:82 CBI, Stockholm, Sweden (1982).
20. Vermeulen Edwin, Balans tussen emissie en opname CO<sub>2</sub>, Hoe zit het nu werkelijk met de CO<sub>2</sub>-emissie en - opname door beton, October (2017).





21. Kapur, A., Keoleian, G., Kendall, A. & Kesler, S. E. Dynamic modeling of In-Use cement stocks in the United States. *J. Ind. Ecol.* 12, 539–556 (2008).
22. Steinour H.H., *The Ultimate Products of the Carbonation of Portland Cement*, SN1136, Portland Cem. Assn, (April 1957).
23. IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.
24. Mineral Products Association for the Department of Energy Security and Net Zero (formerly BEIS), 2023: *UK Greenhouse Gas Inventory Improvement: Carbonation of Concrete Emissions Sink Modelling*. BEIS Tender Reference CR21048.

# Appendix 1 – Characterization of existing CO<sub>2</sub> uptake models

The project has developed an overview of the various national and international models available to calculate the uptake of CO<sub>2</sub> in concrete. These models usually represent more advanced and complex uptake models. Table 31 below presents the different models with references and summary information about each model for comparison.

**Table 31 Overview and characterization of existing models for calculation of CO<sub>2</sub> uptake and their background.**

	Sweden	EN 16757	Norway	Netherlands	Ireland	Switzerland	"Global"	Switzerland 2	Spain
<b>General Framework</b>									
<b>Published</b>	Andersson R. et al, "Calculating CO <sub>2</sub> -Uptake for Existing Concrete Structures during and after Service Life", 2013	Product Category Rules for Concrete and Concrete Elements, 2017	Engelsen and Justnes, "CO <sub>2</sub> binding by Concrete", 2014	Vermeulen E., Balans tussen emissie en opname CO <sub>2</sub> , 2017	Fitzpatrick D. et al, "Sequestration of Carbon Dioxide by Concrete Infrastructure: A Preliminary investigation in Ireland", 2015	Nygaard and Leemann, "Carbon dioxide uptake of reinforced concrete structures due to carbonation", 2012	Xi et al, "Substantial global uptake by cement carbonation", 2016	Leemann, Hunkler, Widmer, "Calculation of CO <sub>2</sub> -binding during service life of concrete", 2018	I. Galán et al, "Summary of the Study of the CO <sub>2</sub> Sink Effect of Cement Based Materials" 2009 I. Galan et al, "Sequestration of CO <sub>2</sub> by concrete carbonation" IECA Editors 2009
<b>Number of references</b>	23	23 in Annex BB on Carbonation	82	8	12	73	71	7	44
<b>View</b>	Country/society	Single product in future	Country/society	Country/society	Country/society	Product and country/society (Uptake in the total production during 50 years)	Global/society	Product (country/society)	
<b>Perspective</b>	Annual uptake	(PCR/EPD)	Annual uptake	Annual uptake	Annual uptake		Uptake 1930-2013		Uptake at 50 and 100 year
<b>Base</b>	Clinker consumption, historical 100 years	Clinker content in the product	Present cement consumption, 100 years future uptake	Cement consumption,	Clinker consumption, historical 40 years	Cement (clinker) consumption 2010	Cement consumption, historical 1930-2013, in four regions: China, US, Europe, rest of the world		Cement production
<b>Constituents participating in the uptake</b>	Uptake in clinker	Uptake in clinker	Uptake in CEM I, CEM II/A-V and CEM II/B-S	Uptake in CEM I (clinker) and in slag	Uptake in clinker	Uptake in clinker	Cement without specification. Cement kiln dust.	Uptake in CEM I, CEM II/A and CEM II/B	Clinker and fly ashes, limestone. Pozzolan and slags



Report B2499 CO<sub>2</sub> uptake in cement-containing products – Background and calculation models for implementation in national greenhouse gas emission inventories

	Sweden	EN 16757	Norway	Netherlands	Ireland	Switzerland	"Global"	Switzerland 2	Spain
<b>FA and slag</b>	Not taken into account	Taken into account in calculation of carbonation depth, but not for CO <sub>2</sub> uptake	Taken into account	Slag taken into account for both carbonation depth and uptake (0.14 kg CO <sub>2</sub> /kg slag)	Not taken into account	Not relevant	Only clinker content accounted	Not specified	YES included
<b>Maximum uptake value</b>	(Degree of carb)×(emission at calcination of clinker)	(Degree of carb) ×(emission at calcination of clinker)	(Degree of carb)×(emission at calcination of clinker + 70 % of uptake in CaO of slag)	(Degree of carb)×(emission at calcination of clinker + 0,14 kg CO <sub>2</sub> /kg of slag)	(Degree of carb)×(emission at calcination of clinker)	(Degree of carb)×(emission at calcination of clinker)	(Degree of carb)×(emission at calcination of clinker)		Degree of carbonation by carbonated cement
<b>Calcination emissions (kg CO<sub>2</sub>/tonne cement)</b>	CEM I 494 (CEM II 455)	Based on actual clinker content (CaO set to 65 % of clinker)	CEM I 471, CEM II/A-V 396, CEM II/B-S 332	CEM I 490, slag 0	CEM I 479, CEM II/A 428	508 kg/tonne clinker (CEM I 483, CEM II/A 406)	"Process" emissions (calcination) 1930-2013 is 10.4 GtC	CEM I 474, CEM II/A 413, CEM II/B 357	Takes value of other works 550 kg/tonne clinker
<b>Results</b>									
<b>Methods CO<sub>2</sub> uptake</b>	300 ktonne/year 2011, (125 kg/tonne cement)		140 ktonne/year 2011 (165 including recovery phase) (70 resp. 83 kg/tonne cement)	365 ktonne/year 2015 (90 kg/tonne cement). Uptake in recycling stage 83 ktonne (21 kg/tonne cement) Adjustment 75 ktonne resp. 18 kg/tonne cement)	150 ktonne/year 2011 (estimated from the value 75 kg/tonne cement)	No absolute values presented, only relative.	Global uptake 2013 is 0.24 GtC. Uptake 1930-2013 is 4.5 Gt C.1 billion tons/year 2013 (250 kg/tonne cement)	No absolute values presented, only relative	Several quantities in function of type of concrete and exposure class
<b>Calculated as</b>	Uptake in existing building stock, estimated with the previous 100 years cement consumption		Uptake in the 2011 production of concrete during coming 100 years	Uptake in 2015 production of concrete during coming 60 years.	Uptake in one year production of concrete during coming 100 years	Uptake in one year production of concrete during coming 50 years	Uptake in existing building stock, estimated with the previous years (1930-2013) cement consumption	Uptake in one year production of concrete during coming 100 years	Calculated as % of clinker fabrication INCLUDING THE FUEL (multiply by 1.7 the results for referring to decarbonation only
<b>Corresponding to</b>	17 % of production emissions year 2011		15 % of production emissions (18 % including recovery)	19 % of production (incl. import) emissions (23 % including end of life stage)	16 % of calcination emissions, corresponding to about 10 % of total.	Declared to be 10 % of the total emissions, corresponding to $(1/0.63) \times 10 = 16\%$ of the calcination emissions.	Uptake 1930-2013 corresponds to 43 % of calcination emissions	17 % of calcination emissions	2.7 % of emitted CO <sub>2</sub> by decarbonation
<b>Sensitivity</b>	Macro calculation can be overestimated a single year but not over time						Uncertainty analysis carried out.		Surface/volume ratio was calculated for several elements and the carbonation rates were experimental values

	Sweden	EN 16757	Norway	Netherlands	Ireland	Switzerland	"Global"	Switzerland 2	Spain
<b>Accuracy</b>	Known method and input data based on measurements	Known method and input data based on measurements	Known method and input data based on measurements	Known method and input data based on measurements	Conservative assumptions	Reduction with a factor 1.5 according to later paper by Leemann And Hunkler, "Carbonation of concrete: assessing the CO <sub>2</sub> -uptake, 2016.	Known method and input data based on measurements		Conservative assumptions
<b>Carbonation theory</b>									
<b>Carbonation model references</b>	Lagerblad and others. Nilsson	Lagerblad and others	Lagerblad and others. Nilsson (covered conc.)	Lagerblad and others	Silva et al (2014)	Lagerblad and others	Lagerblad and others		Various and own models
<b>Depth of carbonation model</b>	$d = k t^{1/2}$ Polynomial expressions for covered concrete. $d = f(t_2, t, t^{1/2})$	$d = k t^{1/2}$	$d = k t^{1/2}$ Polynomial expressions for covered concrete. $d = f(t_2, t, t^{1/2})$	$d = k t^{1/2}$	Formula for RH less than 70 %, modified by factors 1.0 for internal, 0.5 external sheltered and 0.3 external exposed to rain.	$d = k t^{1/2}$	$d = k t^{1/2}$		$d = k t^{1/2}$
<b>Exposure classes</b>	11	6	6	5	Residential 6, Civil engineering 3, Commercial 7		5		Standard: interior, outdoors sheltered and non-sheltered from rain
<b>Strength classes</b>	4	4	4	7	5	3 (?)	4		2 concretes and paste
<b>Carbonation degree</b>	50-90 %, specified for each exposure	40-85 %, specified for each exposure	70 %	40-85 %, specified for each exposure	Not specified	75 %, changed to 50 % in the paper of Leemann and Hunkler, cf "Accuracy" above.	80 % for concrete 91.5 % for mortar/render/plaster		Main aim of the study
<b>Concrete data</b>									
<b>No. of applications (type of product)</b>	7	Single structures/products	24	5	3	20	Depending on region, most detailed from China		Concrete elements in general
<b>Total no of product exposures (scenarios)</b>	33	Infinite	54	25	14	31	Depending on region, most detailed from China		3
<b>Application surface/volume</b>	Calculated for each application	Actual structure	Calculated for each application	Calculated for each application	Calculated for each application	Calculated for each application	Calculated for each application		Calculated with detail
<b>"special case"</b>	overlapping corner						Mortar/render/plaster and cement kiln dust		No recycling, no secondary use or mortar/render/plaster application
<b>Historical use of concrete in different applications, based on statistic</b>	60 years (100 years with less accuracy)		Not applied (use 2011 provided)	Not applied (no change in consumption during	40 years	Not applied	Depending on region, US 1997-2005, China 1996-2012, Europe		Yes, several ages were studied



Report B2499 CO<sub>2</sub> uptake in cement-containing products – Background and calculation models for implementation in national greenhouse gas emission inventories

	Sweden	EN 16757	Norway	Netherlands	Ireland	Switzerland	"Global"	Switzerland 2	Spain
				the years is assumed, 2015 is the basis)			(nordic countries.) 2003.		
	Sweden	EN 16757	Norway	Netherlands	Ireland	Switzerland	"Global"	Switzerland 2	Spain
<b>End of calculation</b>	See maximum uptake value	See maximum uptake value	See maximum uptake value	See maximum uptake value	See maximum uptake value	50 years, see remark below			50 years for buildings and 100 years for infrastructure
<b>End-of-life and secondary use</b>									
<b>End of life processes</b>	Demolished, crushed, stockpiled and reused as unbound material	Demolished, crushed, and stockpiled. Reuse only as additional information	Demolished, crushed, stockpiled and reused as unbound material	Demolished, crushed, stockpiled, and reused.	Only shortly treated	Demolished, crushed, stockpiled, and reused.	Demolished, crushed, and secondary use. Only small uptake		No recycling or secondary use
<b>Demolished and crushed, % of annual production</b>	8 %		10 %	35 % (5.1 m <sup>3</sup> recycled/14 m <sup>3</sup> produced)		Scenarios of 0, 40, 60 and 100 % recycled			no
<b>% recycled</b>	Existing	National provisions	10 % of annual concrete production	35 %		Scenarios of 0, 40, 60 and 100 % recycled	China 3 %, USA 60 %, Europe 61 %, ROW 25 %		no
<b>Stored to increase uptake</b>	Potential given	Potential given							no
<b>Remark</b>	Uptake during one year (2011) in existing buildings is calculated from 100 years cement statistics and 60 years concrete application statistics		Uptake during one year in existing buildings is supposed to be equal to the uptake during 100 years in one year (2011) concrete production.	Uptake during one year in existing buildings is supposed to be equal to the uptake during 60 years in one year (2015) concrete production. Concrete blocks are responsible for a significant proportion (24 %) of the CO <sub>2</sub> uptake.	Uptake during one year in existing buildings is supposed to be equal to the uptake during 100 years in one year concrete production. Open texture concrete blocks and roof tiles are responsible for a significant proportion of the CO <sub>2</sub> uptake	The uptake figure 16 % of the calcination emissions should according to the later recommendations be reduced by a factor 1.5, that is to 10.7 %. In order to be consistent with the methods in the other countries a 100 years perspective should be applied, resulting in 1.414×10.7=15 %	Uptake during 1930-2013 as well as present (2013). Uptake in mortar/render/plaster is significantly contributing to the large figures	This more recent but short report, present values for typical Swiss concrete house building applications	The low uptake value of 2.7 % is adjusted in a later report to 15 %. [9]

## Appendix 2 – Literature overview of carbonation

Uptake of CO<sub>2</sub> in concrete through carbonation is not a new research field. Carbonation has been known for a long time and extensive research exists in the field. Originally, the research was conducted to understand how carbonation affects the properties of concrete. The formation of carbonates in the concrete makes concrete stronger, but reduces the pH of the concrete, which affects the corrosion properties of the reinforcement bars. Later research on carbonation of concrete has a stronger focus on analyzing the total CO<sub>2</sub> balance for cement and concrete. In Appendix 2, we want to show the research width that exists in the field as a complement and a basis for the model studies that have been carried out in this study.

- A1. A. M. Zhu, Concrete carbonation and the durability of reinforced concrete, *Concrete*, 6(1992):18-22. (in Chinese)
- A2. Alexander, M. G., Mackechnie, J. R., & Yam, W. (2007). Carbonation of concrete bridge structures in three South African localities [Open Access]. *Cement and Concrete Composites*, 29(10), 750–759. <https://open.uct.ac.za/bitstreams/5620947c-927b-458f-a938-4611df398889/download>
- A3. Ali, A., Dunster, A., Durability of reinforced concrete -effects of concrete composition and curing on carbonation under different exposure conditions. BRE-report, Garston UK 1998.
- A4. Al Salaheen, M., Alaloul, W. S., Alzubi, K. M., Malkawi, A. baha A., & Musarat, M. A. (2023). Advancing waste-based construction materials through carbon dioxide curing: A comprehensive review [Open Access]. *Results in Engineering*, 20, 101591. <https://doi.org/10.1016/j.rineng.2023.101591>
- A5. Andrade C., Evaluation of the degree of carbonation of concretes in three environments, *Construction and Building Materials*, Volume 230, 10 January 2020, 116804.
- A6. Andersson, R., Fridh, K., Stripple, H. & Häglund, M. Calculating CO<sub>2</sub> uptake for existing concrete structures during and after service life. *Environ. Sci. Technol.* 47, 11625–11633 (2013).
- A7. Ann, K. Y., Pack, S.-W., Hwang, J.-P., Song, H.-W., & Kim, S.-H. (2010). Service life prediction of a concrete bridge structure subjected to carbonation. *Construction and Building Materials*, 24(8), 1494–1501. <https://doi.org/10.1016/j.conbuildmat.2010.01.023>
- A8. Barcelo, L., Kline, J., Walenta, G. & Gartner, E. Cement and carbon emissions. *Mater. Struct.* 47, 1055–1065 (2014).
- A9. Bary, B., Sellier, A., Coupled-carbon dioxide-calcium transfer model for carbonation of concrete. *Cem. Concr. Res.* 34, pp 1859-1872, 2004.
- A10. Beijing Local Standard - Technical Specifications for Application of Dry-mixed Mortar DB11/T696-2009, J11582-12010 (Housing and Urban Rural Construction Standard Quota Division, 2010).
- A11. Berner, R. A., Lasaga, A. C. & Garrels, R. M. The carbon-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. *Am. J. Sci.* 283, 641–683 (1983).
- A12. Bobicki, E. R., Liu, Q., Xu, Z. & Zeng, H. Carbon capture and storage using alkaline industrial wastes. *Prog. Energy Combust. Sci.* 38, 302–320 (2012).

- A13. Boden, T. A., Marland, G. & Andres, R. J. Global, Regional, and National Fossil-Fuel CO<sub>2</sub> Emissions (Carbon Dioxide Information Analysis Center, 2014).
- A14. Böhm, M., Kropp, J., Muntean, A., A two-reaction-zones moving-interface model for predicting Ca(OH)<sub>2</sub> carbonation in concrete, Zentrum für Technomathematics, Fachbereich 3-Mathematics and Information, Report 03-04, Universität von Bremen, 2003.
- A15. Borges, P. M., Schiavon, J. Z., da Silva, S. R., Rigo, E., Neves Junior, A., Possan, E., & Andrade, J. J. de O. (2023). Mortars with recycled aggregate of construction and demolition waste: Mechanical properties and carbon uptake. *Construction and Building Materials*, 387, 131600. <https://doi.org/10.1016/j.conbuildmat.2023.131600>
- A16. Bossink, B. & Brouwers, H. Construction waste: quantification and source evaluation. *J. Constr. Eng. Manage.* 122, 55–60 (1996).
- A17. Browner, R. Design prediction of the life for reinforced concrete in marine and other chloride environments. *Durability Build. Mater.* 1, 113–125 (1982).
- A18. Bui, H., Delattre, F., & Levacher, D. (2023). Experimental Methods to Evaluate the Carbonation Degree in Concrete—State of the Art Review [Open Access]. *Applied Sciences*, 13(4), Article 4. <https://doi.org/10.3390/app13042533>
- A19. Cement Statistics and Information (USGS, 2015); <http://minerals.usgs.gov/minerals/pubs/commodity/cement/index.html>
- A20. Cemsuisse (2016): EPD for four types of Swiss cements. <http://www.cemsuisse.ch/cemsuisse/ueberuns/publikationen/epd/index.html?lang=de>
- A21. Chang, C.-F. & Chen, J.-W. The experimental investigation of concrete carbonation depth. *Cement Concr. Res.* 36, 1760–1767 (2006).
- A22. Chen, J.J., Thomas, J.J., Taylor, H.W.F., Jennings, H.M., Solubility and structure of calcium silicate hydrate, *Cem. Conc. Res.* Vol 34, pp 1499-1521, 2004.
- A23. Clear, C. A.; de Saulles, T., BCA Recarbonation Scoping Study: British Cement Association: Camberly, UK, 2007.
- A24. CO<sub>2</sub> Emissions from fuel combustion (International Energy Agency, 2014).
- A25. Concrete-Part 1. Specification, Performance, Production and Conformity EN 206-1-2000 (European Committee for Standardization, 2001).
- A26. Currie, R. J., Carbonation depth in structural-quality concrete, BRE report, Garston, UK 1986.
- A27. Dodoo, A., Gustavsson, L. & Sathre, R. Carbon implications of end-of-life management of building materials. *Resour. Conserv. Recy.* 53, 276–286 (2009).
- A28. Eggleston, S., Buendia, L. & Miwa, K. 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 3 Industrial Processes and Product Use (Institute for Global Environmental Strategies, 2006).
- A29. Eggleston, S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. IPCC Guidelines for National Greenhouse Gas Inventories (Institute for Global Environmental Strategies, 2006).
- A30. Ekolu, S. O. (2012). Model verification, refinement and testing on independent 10-year carbonation field data. 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR 2012, September 3, 2012 - September 5, 2012, 445–450.
- A31. Ekolu, S. O. (2016). A review on effects of curing, sheltering, and CO<sub>2</sub> concentration upon natural carbonation of concrete. *Construction and Building Materials*, 127, 306–320. <https://doi.org/10.1016/j.conbuildmat.2016.09.056>
- A32. El-Turki, A., Carter, M. A., Wilson, M. A., Ball, R. J. & Allen, G. C. A microbalance study of the effects of hydraulicity and sand grain size on carbonation of lime and cement. *Const. Build. Mater.* 23, 1423–1428 (2009).
- A33. EN 16757 (June 2017): Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements.

- A34. Engelsen C.J., Mehus J., Pade C. and Sæther D.H., Carbon dioxide uptake in demolished and crushed concrete, Norwegian Building Research Institute, Project report 395, 2005, 38 pp. ISBN 82-536-0900-0.
- A35. Fridh and Lagerblad. Carbonation of Indoor Concrete, report TVBM-3169; Lund University, 2013.
- A36. Fukushima, T., Theoretical investigation on the influence of various factors on carbonation of concrete, Building research Institute (Japan), BRI Research Paper No 127 (ISSN 0453-4972), Japan, 1988.
- A37. G. A. Meehl, T. F. Stocker, W. D. Collins, et al, Global climate projections. In: Climate change 2007: The physical science basis [R], Cambridge University, 2007.
- A38. Gabrilová, A., Havlica, J., Sahu, S., Stability of calciumaluminat hydrates in water solution with different pH, Cem. Conc. Res., 21, 1023-1027, 1991.
- A39. Gajda J., Absorption of Atmospheric Carbon Dioxide by Portland Cement, R&D Serial No. 2255a, Portland Cement Association, Skokie, Illinois, USA, 2001.
- A40. Gajda, J., Miller F. M., Concrete as a Sink for Atmospheric Carbon Dioxide: a Literature Review and Estimation of CO<sub>2</sub> Absorption by Portland Cement Concrete, R&D Serial No. 2255, Portland Cement Association, Skokie, Illinois, USA, 2000.
- A41. Galán I. et al., Estudio del efecto sumidero de CO<sub>2</sub> de los materiales de base cemento, Cemento Hormigón, ISSN 0008-8919, N<sup>o</sup>. 939, 2010, págs. 70-83. (in Spanish)
- A42. Galán I., Andrade C., Mora P., Sanjuan M.A., Lopez-Agtti J.C., Prieto M., Summary of the Study of the CO<sub>2</sub> Sink Effect of Cement Based Materials, English translation and summary of the Spanish report "Estudio del Efecto Sumidero de CO<sub>2</sub> de los Materiales de Base Cemento", Spain, 2009.
- A43. Galán, I., Andrade, C., Mora, P. & Sanjuan, M. A. Sequestration of CO<sub>2</sub> by concrete carbonation. Environ. Sci. Technol. 44, 3181–3186 (2010).
- A44. García-Segura, T., Yepes, V., & Alcalá, J. (2014). Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability [Open Access]. The International Journal of Life Cycle Assessment, 19(1), 3–12. <https://doi.org/10.1007/s11367-013-0614-0>
- A45. Gaztañaga, M. T. (1996). "Influencia de la carbonatación en la microestructura de diferentes pastas de cemento hidratadas." PhD. Universidad Complutense de Madrid. Spain.
- A46. GB/T50476-2008, Code for the durability design of concrete structures, China Architecture & Building Press, Beijing, 2008. (in Chinese)
- A47. GB50010-2008, Code for the design of concrete structures, China Architecture & Building Press, Beijing, 2010. (in Chinese)
- A48. GB50068-2001, Unified standard for the reliability design of building structures, China Architecture & Building Press, Beijing, 2001. (in Chinese)
- A49. Greve-Dierfeld, S von (2015): Bemessungsregeln zur Sicherstellung der Dauerhaftigkeit XC-exponierter Stahlbetonbauteile. Diss., Technical University Munich, Munich.
- A50. Guidelines for green concrete structures Category: Guide to good practice, fib Bulletin No. 67, 2012, ISBN: 978-2-88394-107-6.
- A51. Guiglia, M., & Taliano, M. (2013). Comparison of carbonation depths measured on in-field exposed existing r.c. Structures with predictions made using fib-Model Code 2010. Cement and Concrete Composites, 38, 92–108. <https://doi.org/10.1016/j.cemconcomp.2013.03.014>
- A52. H. B. Xie, Y. F. Wang, X. Y. Yang, et al, Influence of climate change on reliability of RC structure under carbonization, Journal of Beijing Jiaotong University, 1(2015): 72-77. (in chinese)
- A53. Habert G (2015): Carbonation of recycled concrete in relation with TC 229, ETH Zürich, Zürich.



- A54. Hagberg L., Karlsson P. E., Stripple H., Ek M. Zetterberg T. Zetterberg L. Svenska skogsindustrins emissioner och upptag av växthusgaser Swedish Forest Industry Emissions and Removals of Greenhouse Gases, IVL-report B1774 (2008).
- A55. Häkkinen, T., Influence of high slag contents on the basic mechanical properties and carbonation of concrete. VTT publications No141, Espoo, Finland, 1993.
- A56. Han-Seung Lee, Xiao-Yong Wang, Evaluation of the Carbon Dioxide Uptake of Slag-Blended Concrete Structures, Considering the Effect of Carbonation, Sustainability 2016, 8, 312; doi:10.3390/su8040312.
- A57. Haselbach, L., & Alam, A. (2015). Carbon Sequestration in Old and New Portland Cement Concrete Pavement Interiors. Innovative Materials and Design for Sustainable Transportation Infrastructure, 71–82. <https://doi.org/10.1061/9780784479278.007>
- A58. Haselbach, L. Potential for carbon dioxide absorption in concrete J. Environ. Eng., ASCE, June 2009.
- A59. Hawkins, G. J., Bhatti, J. I. & O'Hare, A. T. in Innovations in Portland Cement Manufacturing (eds Bhatti, J. I., Miller, F. M. & Kosmatka, S. H.) 735–779 (Portland Cement Association, 2004).
- A60. Hedenblad, G., Moisture permeability for mature concrete. Report TVBM-1044, Division of building materials, Lund Institute of Technology, Lund Sweden, 1993.
- A61. Hoffmann C, Jacobs F (2007): Recyclingbeton aus Beton- und Mischabbruchgranulat – Sachstandsbericht. EMPA & TFB (in German).
- A62. Ho, H.-J., Izumi, Y., & Iizuka, A. (2024). A CO<sub>2</sub> removal technology based on mineral carbonation and the stability of product carbon storage in a cement matrix [Open Access]. Environmental Technology and Innovation, 34. <https://doi.org/10.1016/j.eti.2024.103623>
- A63. Houst, Y. F.; Wittmann, F. H. Depth profiles of carbonates formed during natural carbonation. Cem. Concr. Res. 2002, No. 32, 1923–1930.
- A64. Hu, M., Bergsdal, H., van der Voet, E., Huppel, G. & Müller, D. B. Dynamics of urban and rural housing stocks in China. Build. Res. Inf. 38, 301–317 (2010).
- A65. Huang, N., Chang, J. & Liang, M. Effect of plastering on the carbonation of a 35-year-old reinforced concrete building. Const. Build. Mater. 29, 206–214 (2012).
- A66. Huang, T., Shi, F., Tanikawa, H., Fei, J. & Han, J. Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. Resour. Conserv. Recy. 72, 91–101 (2013).
- A67. Huang, Z., Wang, J., Bing, L., Qiu, Y., Guo, R., Yu, Y., Ma, M., Niu, L., Tong, D., Andrew, R. M., Friedlingstein, P., Canadell, J. G., Xi, F., & Liu, Z. (2023). Global carbon uptake of cement carbonation accounts 1930–2021. Earth System Science Data, 15(11), 4947–4958. <https://doi.org/10.5194/essd-15-4947-2023>
- A68. Huang, Z. & Zhao, J. Concrete Mix Proportion Quick Manual (China Building Industry, 2001).
- A69. Hunkeler F, Lamar L (2012): Anforderungen an den Karbonatisierungswiderstand von Betonen, Forschungsauftrag AGB 2008/012, Arbeitsgruppe Brückenforschung (AGB), Bericht 649, Bern.
- A70. Hunkeler, F (2016): Swiss requirements for the carbonation resistance of concrete for the exposure classes XC3, XC4 and XD1, 9th International Concrete Conference 2016, 4-6 July 2016, Dundee, Scotland.
- A71. Huntzinger, D. N., Gierke, J. S., Kawatra, S. K., Eisele, T. C. & Sutter, L. L. Carbon dioxide sequestration in cement kiln dust through mineral carbonation. Environ. Sci. Technol. 43, 1986–1992 (2009).
- A72. I. S. Yoon, O. Copuroglu, K. B. Park, Effect of Global climatic change on carbonation progress of concrete, Atmospheric Environment, 34(2007): 7274-7285.

- A73. J. X. Peng, X. D. Shao, J. R. Zhang, Climate change, CO<sub>2</sub> emission scenarios and effects on carbonation-induced cracking and time-dependent reliability of reinforced concrete structures, *Chian Civil Engineering Journal*, 6(2010):74-81. (in chinese)
- A74. Jacobsen, S.; Jahren, P. Binding of CO<sub>2</sub> by Carbonation of Norwegian OPC Concrete; CANMET/ACI International Conference on Sustainability and Concrete Technology: Lyon, 2002.
- A75. Jo, Y. K. Basic properties of epoxy cement mortars without hardener after outdoor exposure. *Constr. Build. Mater.* 22, 911–920 (2008).
- A76. Johannesson, B. & Utgenannt, P. Microstructural changes caused by carbonation of cement mortar. *Cement Concr. Res.* 31, 925–931 (2001).
- A77. Johannesson, B. F. A theoretical model describing diffusion of a mixture of different types of ions in pore solution of concrete coupled to moisture transport. *Cem. Concr. Res.* 2003, 33 (4), 481–488.
- A78. Jonsson, G. & Wallevik, O. Information on the use of concrete in Denmark, Sweden, Norway and Iceland. *Icelandic Build. Res. Inst.* (2005).
- A79. Jonsson, G. Information on the Use of Concrete in Denmark, Sweden, Norway and Iceland; Icelandic Building research Institute: Reykjavik, 2005; ISBN: 9979-9174-7-4.
- A80. Junting Jiao, Bo Diao and Chenfei Wang, The Carbonation Model of Concrete Structures and Its Application, International Conference on Civil, Transportation and Environment (ICCTE 2016).
- A81. Kapur, A., Keoleian, G., Kendall, A. & Kesler, S. E. Dynamic modeling of In-Use cement stocks in the United States. *J. Ind. Ecol.* 12, 539–556 (2008).
- A82. Karimi, A., Ghanooni-Bagha, M., Ramezani, E., Shirzadi Javid, A. A., & Zabihi Samani, M. (2023). Influential factors on concrete carbonation: A review. *Magazine of Concrete Research*, 75(23), 1212–1242. <https://doi.org/10.1680/jmacr.22.00252>
- A83. Kelly, T. D. & Matos, G. R. Historical Statistics for Mineral and Material Commodities in the United States (United States Geological Survey Data, 2014) <http://minerals.usgs.gov/minerals/pubs/historical-statistics/nickel-use.pdf>
- A84. Kelly, T. D. Crushed Cement Concrete Substitution for Construction Aggregates, a Materials Flow Analysis (US Department of the Interior, US Geological Survey, 1998).
- A85. Khanna, O. S. Characterization and Utilization of Cement Kiln Dusts (CKDs) as Partial Replacements of Portland Cement PhD thesis, Univ. Toronto (2009).
- A86. Khunthongkeaw, J., Tangtermsirikul, S., & Leelawat, T. (2006). A study on carbonation depth prediction for fly ash concrete. *Construction and Building Materials*, 20(9), 744–753. <https://doi.org/10.1016/j.conbuildmat.2005.01.052>
- A87. Kikuchi T, Kuroda Y. Carbon dioxide uptake in demolished crushed concrete. *Journal of Advanced Concrete Technology* 9: 115-124 (2011).
- A88. Kjellsen K. O.; Guimaraes M., Nilsson A. The CO<sub>2</sub> Balance of Concrete in a Life Cycle Perspective; Danish Technological Institute, DTI: Taastrup, Denmark, 2005; ISBN: 87-7756-758-7.
- A89. Klopfer, H. The carbonation of external concrete and how to combat it. *Bautenschutz Bausanieruniz* 3, 86–97 (1978).
- A90. Ko, K., Jeong, J., & Chung, H. (2023). Embedded-type optical sensors for in situ monitoring of carbonation of cementitious materials. *Construction and Building Materials*, 371, 130646. <https://doi.org/10.1016/j.conbuildmat.2023.130646>
- A91. Kropp, J., *Karbonatisierung und Transportvorgänge in Zementstein*, Dissertation Universität Karlsruhe, Karlsruhe, Germany 1983.
- A92. Kuroda, Y and Kikuchi, T. Uptake of Carbon Dioxide in the Demolished and Crushed Concrete; *Concrete Research and Technology*, 2009; Vol. 20, No. 1.

- A93. L. P. Xu, Sh. Y. Huang, A mathematical model of predicting concrete carbonation depth, *Journal of Shanghai Institute of building materials*, 4(1991):347-356. (in chinese)
- A94. Lagerblad B., Ghonei, G., Deterioration of transmission line foundations in Abu Dhabi -Life Time prediction of concrete in hot and arid climate, *Proceedings, 7th International Conference, Concrete in Hot & Arid Clima*, 15 pp, 13-15 October, 2003, Bahrain, 2003.
- A95. Lagerblad Björn, Carbon dioxide uptake during concrete life cycle – State of the art, Swedish Cement and Concrete Research Institute (CBI), CBI Report 2:2005 ISBN 91-976070-0-2, ISSN 0346-8240 (2005).
- A96. Lagerblad, B., Jennings, H.M., Chen, J.J Modification of cement paste with silica fume-A NMR Study, *Proceedings 1st International Symposium on Nanotechnology in Construction*, Paisly june 2003, The Royal Society of Chemistry (RSC). Special publication No 292, 2004. pp 123-135 2004.
- A97. Lagerblad, B., Leaching performance of concrete based on samples from old concrete constructions, SKB TR-01-27, Report series of Swedish Nuclear Fuel and Waste Management CO, Stockholm, Sweden, 2001.
- A98. Lagerblad, B., Leaching performance of concrete based on studies of old submerged concrete., *Proceedings, Sixth CanMet/ACI Intrnational conference on durability of Concrete*, Thessaloniki, Greece 2003. Supplementary papers, pp 195-211.
- A99. Leber I., Blakey F.A. (1956). "Some effects of carbon dioxide on mortars and concrete." *Journal of the American Concrete Institute* 53, 295-308.
- A100. Leemann & Hunkeler (2016): Carbonation of concrete: assessing the CO<sub>2</sub>-uptake. cemsuisse-Projekt 201602  
[http://www.cemsuisse.ch/cemsuisse/forschung/forschungsberichte/berichte\\_2016/index.html?lang=de](http://www.cemsuisse.ch/cemsuisse/forschung/forschungsberichte/berichte_2016/index.html?lang=de)
- A101. Leemann A & Moro F (2017) Carbonation of concrete: the role of CO<sub>2</sub> concentration, relative humidity and CO<sub>2</sub> buffer capacity. *Materials and Structures* 50:30.
- A102. Leemann A & Nygaard, P (2014) Zusammenhang zwischen Karbonatisierungswiderstand, CO<sub>2</sub>-Pufferkapazität und Diffusivität von Mischzementen, cemsuisse-Project 201207, Bern (in German).
- A103. Leemann A, Nygaard P, Kaufmann J, Loser R (2015) Relation between carbonation resistance, mix design and exposure of mortar and concrete. *Cement and Concrete Composites* 62:33-43.
- A104. Leemann A., Hunkeler F., Carbonation of concrete: assessing the CO<sub>2</sub>-uptake., cemsuisse project 201602 (12-08-2016).
- A105. Liang, M. T., Qu, W-J., Liao, Y.S., A study of carbonation in concrete structures at existing cracks, *Journ. Chinese Inst. of Eng.* Vol 23, No 2, pp 143-153, 2000.
- A106. Li, P., Shi, T., Bing, L., Wang, Z., & Xi, F. (2021). Calculation method and model of carbon sequestration by urban buildings: An example from Shenyang. *Journal of Cleaner Production*, 317, 128450. <https://doi.org/10.1016/j.jclepro.2021.128450>
- A107. Lo, T. Y., Liao, W., Wong, C. K. & Tang, W. Evaluation of carbonation resistance of paint coated concrete for buildings. *Constr. Build. Mater.* 107, 299–306 (2016).
- A108. Low, M.-S. *Material Flow Analysis of Concrete in the United States* (Massachusetts Institute of Technology, 2005).
- A109. Lu, W. et al. An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Waste Manage.* 31, 680–687 (2011).
- A110. Lu, W. *Waste Recycling System Material Metabolism Analysis Model and Its Application* PhD thesis, Univ. Tsinghua (2010).
- A111. M. G. Stewart, X. M. Wang, M. Nguyen, Climate change impact and risks of concrete infrastructure deterioration, *Engineering Structures*, 4(2011): 1326-1337.

- A112. Maage, M., & Skjølsvold, Karbonatisering av betong med og utan silikastøv, FCB-rapport, STF65 A83090, Trondheim, Norge, 1983.
- A113. Matthews, J., Carbonation of ten years old concretes with and without PFA, Proc AshTech 1984.
- A114. Meland, I. & Trätteberg, A., Karbonatisering i sement med slagg eller silikastøv, FCB Rapport, STF65 A81033, Trondheim, Norge, 1981.
- A115. Meland, I., Karbonatisering i flygaskement og standard portland sement med og utan silika, SINTEF Rapport, STF A85049., Trondheim, Norge, 1985.
- A116. Meyer, Wierig, Husman, Karbonatisierung von Schwerbeton, Deuther Ausschus fur Stahlbetong, Heft 182, Berlin, 1967.
- A117. Monteiro, I., Branco, F., Brito, J. d. & Neves, R. Statistical analysis of the carbonation coefficient in open air concrete structures. Const. Build. Mater. 29, 263–269 (2012).
- A118. Moon, H. Y., Shin, D. G. & Choi, D. S. Evaluation of the durability of mortar and concrete applied with inorganic coating material and surface treatment system. Constr. Build. Mater. 21, 362–369 (2007).
- A119. Multer, B. (2023). Carbon Sequestration via Concrete Weathering in Soil [Open Access] [Thesis, The Ohio State University].  
[http://rave.ohiolink.edu/etdc/view?acc\\_num=osu1681120564894507](http://rave.ohiolink.edu/etdc/view?acc_num=osu1681120564894507)
- A120. N. T. Di, The durability and life prediction of concrete structures, Science Press, Beijing, 2003. (in chinese)
- A121. Nagataki, S., Ohga, H., Kim, E., Effect of curing conditions on carbonation and corrosion in fly ash concrete, ACI SP-91 Madrid, Proc 1986 V1 521-540, 1986.
- A122. New approach to durability design. An example of carbonation induced corrosion., CEB, Bull 238, Lausanne Switzerland, may 1997.
- A123. Nilsson, L. O. A new model for CO<sub>2</sub>-absorption of concrete structures, report TVBM-3158, Lund University, 2011.
- A124. Nisbet, M. A. Environmental Life Cycle Inventory of Portland Cement Concrete (Portland Cement Association Skokie, 2000).
- A125. Nygaard PV, Leemann A (2012) Carbon dioxide uptake of reinforced concrete structures due to carbonation. EMPA, Cemsuisse-Project 201106.
- A126. Otsuki, N., Gallardo, R. S., Annaka, T., Takaki, S., & Nishida, T. (2012). Field survey for carbonation depth of reinforced concrete buildings in the Philippines. 37th Conference on Our World in Concrete & Structures, 29–31. In Japanese.
- A127. Pade C, Guimaraes M (2007) The CO<sub>2</sub> uptake of concrete in a 100 year perspective. Cement and Concrete Research 37:1348-1356.
- A128. Pan, Y. et al. A large and persistent carbon sink in the world's forests. Science 333, 988–993 (2011).
- A129. Papadakis, V. G. Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress. Cement Concr. Res. 30, 291–299 (2000).
- A130. Papadakis, V. G., Vayenas, C. G. & Fardis, M. A reaction engineering approach to the problem of concrete carbonation. AIChE J. 35, 1639–1650 (1989).
- A131. Papadakis, V. G., Vayenas, C. G. & Fardis, M. N. Experimental investigation and mathematical modeling of the concrete carbonation problem. Chem. Eng. Sci. 46, 1333–1338 (1991).
- A132. Papadakis, V. G.; Vayenas, C. G.; et Fardis, M. N. Fundamental modeling and experimental investigation of concrete carbonation. Am. Concr. Inst. Mater. J. 1991, 88, 363–373.
- A133. Parrott L.J. (1991/92). "Carbonation, moisture and empty pores." Advances in Cement Research, 4 (15), 111-118.

- A134. Parrott L.J., Killoh D.C. "Carbonation in a 36 year old in situ concrete." *Cement and Concrete Research*, 19 (4), 649-656 (1989).
- A135. Parrott, L. J. Carbonation, moisture and empty pores. *Adv. Cem. Res.* 1991/92, 4 (15), 111–118.
- A136. Parrott, L.J., A review of carbonation in reinforced concrete, A review carried out by C&CA under a BRE contact. July 1987.
- A137. Piao, S. et al. The carbon balance of terrestrial ecosystems in China. *Nature* 458, 1009–1013 (2009).
- A138. Pihlajavaara S.E., Pihlman E. (1974). "Effect of carbonation on microstructural properties of cement stone." *Cement and Concrete Research* 4, 149-154.
- A139. Pommer K.; Pade C.; *Guidelines: uptake of Carbon Dioxide in the Life Cycle Inventory of Concrete*; Danish Technological Institute: Taastrup, Denmark, 2005; ISBN: 87-7756-757-9.
- A140. Pommer, K. & Pade, C. *Guidelines: Uptake of Carbon Dioxide in the Life Cycle Inventory of Concrete* (Nordic Innovation Centre, 2006).
- A141. Pommer, K., Pade, C., Institut, D. T. & Centre, N. I. *Guidelines: Uptake of Carbon Dioxide in the Life Cycle Inventory of Concrete* (Nordic Innovation Centre, 2006).
- A142. Possan, E., Thomaz, W. A., Aleandri, G. A., Felix, E. F., & dos Santos, A. C. P. (2017). CO<sub>2</sub> uptake potential due to concrete carbonation: A case study. *Case Studies in Construction Materials*, 6, 147–161.
- A143. Rau, G. H., Knauss, K. G., Langer, W. H. & Caldeira, K. Reducing energy-related CO<sub>2</sub> emissions using accelerated weathering of limestone. *Energy* 32, 1471–1477 (2007).
- A144. Ready-Mixed Concrete Industry Statistics 2001–2013 (European Ready Mixed Concrete Organization, 2014); <http://www.ermco.eu>
- A145. Release and Uptake of Carbon Dioxide in the Life Cycle of Cement; European Cement Research Academy, Technical Report TR-ECRA 0004/2008; Duesseldorf, 2008.
- A146. Renforth, P., Washbourne, C. L., Taylder, J. & Manning, D. Silicate production and availability for mineral carbonation. *Environ. Sci. Technol.* 45, 2035–2041 (2011).
- A147. Report to Congress on Cement Kiln Dust (Office of Solid Waste and Emergency Response, 1993).
- A148. Richardsson, M.G., *Carbonation of reinforced concrete-Its causes and management*. CITIS LTD, Dublin, London & New York, 1988.
- A149. Roy, S., Northwood, D. & Poh, K. Effect of plastering on the carbonation of a 19-year-old reinforced concrete building. *Constr. Build. Mater.* 10, 267–272 (1996).
- A150. Saetta A.V, Schrefler B.A., Vitaliani R.V., The carbonation of concrete and the mechanism of moisture, heat and carbon dioxide flow through porous materials, *Cement and Concrete Research* Volume 23, Issue 4, July 1993, Pages 761-772.
- A151. Sanjuán, M. Á., Andrade, C., Mora, P., & Zaragoza, A. (2020). Carbon Dioxide Uptake by Cement-Based Materials: A Spanish Case Study [Open Access]. *Applied Sciences*, 10(1), 339. <https://doi.org/10.3390/app10010339>
- A152. Schaefer, D. A., Gui, H., Xu, J., Schaefer, D. A., Gui, H., & Xu, J. (2024). Sequestration of CO<sub>2</sub> by concrete and natural minerals—Current status, future potential, and additional benefits. *Circular Agricultural Systems*, 4(1). <https://doi.org/10.48130/cas-0024-0007>
- A153. Seneviratne, A. M. G., Sergi, G. & Page, C. L. Performance characteristics of surface coatings applied to concrete for control of reinforcement corrosion. *Constr. Build. Mater.* 14, 55–59 (2000).
- A154. Shi Z, Lothenbach B, Geiker MR, Kaufmann J, Leemann A, Ferreiro S, Skibsted J (2016) Experimental studies and thermodynamic modeling of the carbonation of Portland cement, metakaolin and limestone mortars. *Cement and Concrete Research* 88:60-72.
- A155. Silva, A., Neves, R. & de Brito, J. Statistical modelling of carbonation in reinforced concrete. *Cement Concr. Compos.* 50, 73–81 (2014).

- A156. Smith, P. et al. Biophysical and economic limits to negative CO<sub>2</sub> emissions. *Nat. Clim. Change* 6, 42–50 (2016).
- A157. Sreekrishnavilasam, A., King, S. & Santagata, M. Characterization of fresh and landfilled cement kiln dust for reuse in construction applications. *Eng. Geol.* 85, 165–173 (2006).
- A158. Stark, J., Ludwig, H-M., Freeze-thaw-deiceing salt resistance of concrete containing cement rich in granulated blast-furnace slag. *ACI Materials Journal*, vol 94. No 1. 1997.
- A159. Steinour H.H., *The Ultimate Products of the Carbonation of Portland Cement*, R&D SN1136, Portland Cem. Assn. (April 1957).
- A160. Steinour H.H., "Some effects of carbon dioxide on mortars and concrete-discussion." *Journal of the American Concrete Institute*, 30, 905-907 (1959).
- A161. Stripple Håkan, Greenhouse gas strategies for cement containing products. Part of the research project, CO<sub>2</sub> cycle in cement and concrete. IVL report B 2024, (2013). [www.IVL.se](http://www.IVL.se)
- A162. Stronach, S.A., Glasser, F.P., Modelling of the impact of abundant geochemical components on the phase stability and solubility of the CaO-SiO<sub>2</sub>-H<sub>2</sub>O system at 25 °C, *Advances in Cement Research*, Vol 9, No 36, 167-181, 1997.
- A163. Takano, H. & Matsunaga, T. CO<sub>2</sub> fixation by artificial weathering of waste concrete and coccolithophorid algae cultures. *Energy Convers. Manage.* 36, 697–700 (1995).
- A164. Talukdar, S., Banthia, N., Grace, J. & Cohen, S. Carbonation in concrete infrastructure in the context of global climate change: part 2–Canadian urban simulations. *Cement Concr. Compos.* 34, 931–935 (2012).
- A165. Tamai, T., Kasami, H., Hayashi, S., Masuda, Y., & Kanematsu, M. (2007). Carbonation of concrete in structure of buildings constructed between 1953 and 1985 years [Open Access, Japanese with English Abstract]. *AIJ Journal of Technology and Design*, 13(25), 1–6. <https://doi.org/10.3130/aijt.13.1>
- A166. Technical Specification for Application of Recycled Aggregate JGJ/T 240-2011 (The Department of Housing and Urban–Rural Development, 2011).
- A167. The influence of cement content on the performance of concrete, Discussion Document, The Concrete Society, UK, 1999.
- A168. Thiery M, Dangla P, Belin P, Habert G, Roussel N (2013) Carbonation kinetics of a bed of recycled concrete aggregates: A laboratory study on model materials. *Cement and Concrete Research* 46:50-65.
- A169. Thiery, M. et al. Comment Intégrer Quantitativement La Carbonation Atmosphérique Dans le Bilan-Carbone Des Matériaux Cimentaires?; Association Française du Génie Civil, 2009.
- A170. Thiery, M.; Villain, G.; Platret, G.; Goyer, S.; Clement, J.-L.; Dangla, P. Exemple d'application d'un modèle de carbonatation in situ. *Bull. Lab. Ponts Chaussées* 2007, 270–271, 1–22.
- A171. Tuutti, K., Corrosion of steel in concrete. CBI research 4:82 CBI, Stockholm, Sweden 1982.
- A172. Utgenant P., The influence of ageing on the salt-frost resistance of concrete. PhD thesis Lund University of Technology, Div. of Building materials, Report TVBM-1021, 2004.
- A173. V. C. Papadakis, C. C. Vayenas, M. N. Faradis, Fundamental modeling and experimental investigation of concrete carbonation, *ACI Material Journal*, 88(1991):363-373.
- A174. Walther, H. B. (2023). Recarbonation matters—CO<sub>2</sub> absorption of AAC during its use phase. *Ce/Papers*, 6(2), 246–251. <https://doi.org/10.1002/cepa.2093>
- A175. Wani, S., Selvaraj, T., Faria, P., Mehra, A., & Shukla, R. (2023). Study on ancient green materials and technology used in Udaipur palace, India: An input to abate climate changes in modern construction. *Environmental Science and Pollution Research*, 30(41), 93952–93969. <https://doi.org/10.1007/s11356-023-28785-2>
- A176. W. J Qu, D. P. Chen, A stochastic model of concrete carbonation, *Journal of Tongji University*, 5(2007):577-581. (in chinese)

- A177. W. L. Jin, X. Y. Zhao, *The durability of concrete structures*, Science Press, Beijing, 2002. (in chinese)
- A178. Wierig, H.-J, Long-time studies on the carbonation under normal outdoor exposure. Proceedings of RILEM seminar on the durability of concrete structures under normal outdoor exposure, Hannover, Germany, March 1984.
- A179. Winter, C. & Plank, J. The European dry-mix mortar industry (Part 1). *ZKG Int.* 60, 62–69 (2007).
- A180. X. Y. Di, Y. Zhou, The study on concrete carbonation, Proceedings of the Fourth National Symposium on concrete durability, 1991.11. (in chinese)
- A181. Y. Zhang, L. X. Jiang, A practical mathematical model of concrete carbonation depth based on carbonation mechanism, *Industrial buildings*, 1(1998):16-19. (in chinese)
- A182. Yang, K.-H., Seo, E.-A. & Tae, S.-H. Carbonation and CO<sub>2</sub> uptake of concrete. *Environ. Impact Assess.* 46, 43–52 (2014).
- A183. Yoon, I.-S., Çopuroğlu, O. & Park, K.-B. Effect of global climatic change on carbonation progress of concrete. *Atmos. Environ.* 41, 7274–7285 (2007).
- A184. Yude Pan.; et al. A Large and Persistent Carbon Sink in the World's Forests. *Science* 2011, 333, 988–993.
- A185. Zafeiropoulou, T., Rakanta, E. & Batis, G. Performance evaluation of organic coatings against corrosion in reinforced cement mortars. *Prog. Org. Coat.* 72, 175–180 (2011).
- A186. Zhang, L. Carbonization delay coefficients research of concrete surface coverages [in Chinese]. *J. Xi'an Inst. Metall. Const. Eng.* 21, 34–40 (1989).
- A187. Zhang, L. M., & Jiang, W. H. (1990). A study on carbonation of concrete in natural condition and its correlation with artificial accelerated carbonation. *Xi'an Inst. Metall. Constr. Eng.* 22(3), 207–214.
- A188. Zhou, H. *Construction and Installation Engineering Budget Manual* (China Machine Press, 2003).



IVL Swedish Environmental Research Institute Ltd.

P.O. Box 210 60 // S-100 31 Stockholm // Sweden

Phone +46-(0)10-7886500 // [www.ivl.se](http://www.ivl.se)