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International reporting and application of annual CO2 uptake in concrete

Executive summary for greenhouse gas inventories in line with IPCC guidelines

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

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Introduction and background

The climate change issue is today very important both in an international and national perspective. Many organizations and companies are actively working on climate change issues and greenhouse gas reductions are often an important goal, as well as mapping and monitoring of greenhouse gases. It is therefore of the utmost importance that such greenhouse gas calculations are correct.

Concrete is the single most important building material in society and is used for a variety of important structures, such as houses, bridges, tunnels, roads, roof tiles, and other construction products. After the product's service life, the concrete is normally crushed and recycled as secondary products e.g. in road base course or as fill material. In the production of cement and concrete, CO_2 is formed from combustion of (mainly fossil) fuels and from calcination of the raw materials in the cement kiln. Depending on the CO_2 profile of the fuels, about 36% of the CO_2 emissions emanate from the fuel combustion and the remaining part (64%) comes from the raw material, mainly limestone. A very common estimate is that the use of cement today accounts for about 5-6% of the world's greenhouse gas emissions. Roughly, one can thus estimate that about 3.5% of the global CO_2 emissions are driven off from raw materials by calcination.

However, the calcination reactions in the raw meal/cement are not chemically stable but are reversible in the final concrete. This means that CO_2 in air reacts with hydrated cement phases in the concrete and carbonates are regenerated. This process is usually called carbonation. Theoretical estimations in combination with measurements show that about 75% of the CO_2 from calcination can be taken up in the concrete by carbonation. It is therefore of utmost importance, both for the calculations of national and international emissions and removals, and of environmental performance, that CO_2 uptake in concrete is accounted for. Today, neither the national calculations nor the international reporting to the UNFCCC includes any data for the uptake of CO_2 in concrete. This is a shortcoming that needs to be addressed and the present project is an important part of this work.

Theoretic background to CO_2 uptake in concrete

Portland cement is made mainly of various raw materials such as limestone, clay, marl, silica sand, shale, etc. which are ground and mixed to a raw meal. The main raw material in cement is limestone ($CaCO_3$). In the cement kiln, the raw materials are heated up to about 1450°C and CO_2 is driven off to the atmosphere in the calcination reaction mainly from $CaCO_3$ according to reaction (1).

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2 \qquad (1)$$

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 hydrates (C-S-H) gel and also $Ca(OH)_2$. Thus, both C-S-H gel and $Ca(OH)_2$ form a part of the hardened concrete. CO_2 in the atmosphere, in contact with concrete, will primarily react with $Ca(OH)_2$ in the concrete according to the principle reaction (2) but will also react with the C-S-H gel. These reactions represent the uptake of CO_2 in concrete, which is called carbonation.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (2)$$

Concrete is a porous material that allows both CO_2 in air and water to penetrate into the concrete. The CO_2 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_3^- or CO_3^{2-} 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. Mainly due to the formation of $CaCO_3$ in the concrete, the carbonation rate will slow down with time. Experiments and studies of real structures have shown that the carbonation rate can be assumed to be proportional to the square-root of time (t), $\sqrt{t}$. Other factors that will influence the carbonation rate are porosity of the concrete, w/c ratio, cement type and additions, and surface treatment of the concrete products, which are factors that can readily be estimated, calculated, or are known at national level.

At the end-of-life of concrete products, they are demolished and normally crushed. When the concrete is crushed, new surfaces are created and smaller concrete pieces are formed. This can dramatically increase the carbonation rate if access to CO_2 in air can be maintained. To estimate the uptake of CO_2 in concrete, it is thus important to include both the use stage and end-of-life stage of the concrete products as well as the secondary use of the crushed concrete.

Carbonated concrete is chemically stable and increases the strength of the concrete. The carbonation process is associated with lowering of the pH in the concrete, thus reducing the corrosion protection of built-in steel reinforcement. Therefore, international construction codes have design rules for protection of the reinforcement by, for example, a protecting concrete layer covering the steel rebars, which, in this way, can meet certain criteria based on, for example, climate exposure, material properties, and the designed service life.

International reporting of CO_2 emissions, uptake and other applications

Accurate, robust, and reliable information on anthropogenic greenhouse gas emissions and removals are an essential part to follow-up the national and international emissions, reduction targets, and mitigation measures. Countries report such information to the UNFCCC[1] by annual inventories. Estimated emissions and removals in the inventories are based on methodological guidelines[2] prescribed by the IPCC[3]. The latest version of the IPCC guidelines for national greenhouse gas inventories (from 2006) does not consider CO_2 uptake in concrete and, so far, no data on uptake has been reported by any country to the UNFCCC but similar methods to those proposed here do exist for forestry.

However, the mineral carbonation process has been mentioned briefly in the IPCC guidelines, but also that further work was needed before carbonation could be included into national inventories. Even if the IPCC guidelines does not prescribe methods for carbonation, the reporting to the UNFCCC may include estimations based on other methods, as long as they are properly documented and validated. Today, much more information about carbonation of concrete are available and proposed calculation methods have been developed[4]. CO_2 uptake calculations cannot only be used for international reporting but also for improved calculations of the environmental performance of specific concrete products or in LCA[5] and EPD[6] applications. However, the calculation methodology has to be somewhat modified, for example, in handling of export and import of cement and concrete products in relation to the CO_2 uptake.

Calculation models for uptake of CO_2 in existing concrete structures

Calculating the uptake of CO_2 in all existing concrete during a given year for a specific country (which is necessary for greenhouse gas reporting) is a very complex task if accurate results are to be obtained. Methods for such reporting have been proposed in footnote [4]. These methods are based on previous international research projects for the calculation of national CO_2 uptake and on the IPCC guidelines for emission calculations and removals[2]. Seven studies from different countries have been compiled representing Ireland, the Netherlands, Norway, Spain, Sweden, Switzerland, and "Global".

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[1] United Nations Framework Convention on Climate Change

[2] 2006 IPCC Guidelines for National Greenhouse Gas Inventories

[3] Intergovernmental Panel on Climate Change

[4] Stripple H., Ljungkrantz C., Gustafsson T., Andersson R., CO_2 uptake in cement-containing products - Background and calculation models for IPCC implementation. IVL report B2309 (2018). https://www.ivl.se/english/startpage/pages/publications/publication.html?id=5656

[5] Life Cycle Assessment

[6] Environmental Product Declarations

The IPCC has classified its methodological approaches in three different tiers, according to the quantity of information required, and calculation accuracy. Tier 1 represents a general and simplified approach based on national statistics together with standardized assumptions (factors and parameters) from the IPCC. Tier 1 is also to be used as a starting point to make an early emission or removal estimate of the level of magnitude. Tier 1 can also be used when national information is lacking or if a specific source is considered to be of minor importance/magnitude. The CO_2 uptake values are proposed to be related to the reported calcination emissions from the clinker consumed in the country of concern. For more significant sources, IPCC encourages Tier 2 or Tier 3 with a greater level of granularity. Tier 2 comprise more calculations compared to Tier 1 and applies statistics, factors and parameters, which are more detailed and specific to the country. Tier 3 generally refers to complex models or monitored data (e.g. emission measurements).

Accordingly, three different methods for calculating the annual CO_2 uptake in a country are suggested in footnote [4]. This knowledge is set in line with the IPCC system view, which generally opens up for future inclusion and reporting to the UNFCCC. A total national CO_2 uptake, in the use stage and end-of-life/secondary use stage, of 23% of the national calcination emissions (adjusted for export and import), is proposed as a value for use in Tier 1 today. The uptake of CO_2 in end-of-life/secondary use is today small (~3%) due to the age structure and lifespan of the concrete products. The amount of demolished concrete is however expected to increase, which will increase the potential uptake of CO_2 in the future, see figure 1.

For Tier 2 and 3, methodologies are recommended in footnote[4] for more advanced and accurate calculations. For significant sources, IPCC specify Tier 2 or Tier 3 with a greater level of accuracy. For Tier 2, longer time series of cement consumption data are used (at least 10 years), concrete products covering at least 65 % of the concrete use are identified and specific surfaces are calculated (m^2 surface/m^3 concrete), and the uptake is calculated according to a formula given in standard EN 16757 Annex BB. In Tier 3, computer models are used, which can be based on uptake in all concrete surfaces historically produced with different carbonation condition and an uptake rate reduction proportionally to the square root of time.

In the Swedish study (footnote [7]), a methodology has been used, qualifying for Tier 3. In a specific concrete product, such as roof tiles, or concrete structure applications, such as apartment buildings, there is a dynamic yearly input of new constructions as well as an outflow of constructions that is at the end of its service life. Therefore, a yearly input has to be calculated for each year the products and structures have been used, as well as when they are no longer in use. The annual uptake of CO_2 may be described by Eq. (3) where the annual uptake ΔCO_2 in year t is equal to the difference between the accumulated uptake at the end of year t and (t-1), respectively.

$$\Delta CO_2 = CO_2^{\text{uptake in year t}} = \sum CO_2^{\text{uptake,(t)}} - \sum CO_2^{\text{uptake,(t−1)}} \qquad (3)$$

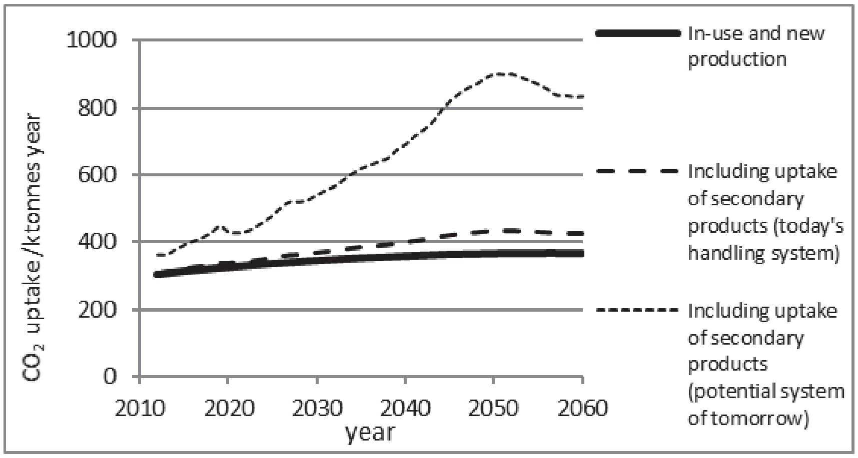

Figure 1. Calculation of a future scenario for CO_2-uptake in Sweden[7].

Future development for application of CO_2 uptake in concrete

In order to speed up the improvement work on the reporting of greenhouse gas emissions and removals, it is proposed that a selected number of countries start calculating and using the uptake of CO_2 in concrete on a national basis and for reporting to the UNFCCC. Even if no calculation methods or reporting structure for uptake of CO_2 in concrete is provided by the IPCC or the UNFCCC, countries can choose to include such information in their National Inventory Reporting (NIR). The NIR contains detailed descriptive and numerical information on anthropogenic emissions and removals. The UNFCCC can then process this data material and include it in the future climate work.

In this project, the above proposed calculation methods could be tested and evaluated in the selected countries. Based on the results of these tests, a broader international implementation with different calculation support can then be planned. Future support may also include the development of a common software to simplify the calculations, especially related to Tier 3 calculations. The work in this project is to be carried out during 2019 (possibly prolonged to spring 2020), in close cooperation with the national cement industries and the national greenhouse gas emission inventory teams.

During the project, bilateral and/or multilateral discussions and meeting between IVL and the different countries will be held through emailing, Skype and/or telephone. If needed, multilateral discussions will be held on the different national circumstances and data availability in relation to the different proposed methods. In this initial project, the goal is to develop at least Tier 1 calculations and, if data and human resources are available, possibly Tier 2 calculations. At the end of the project, if needed, the tier methods will be modified based on the discussions during the different national case studies.

Based on the outcome of the country case studies, IVL will also aim at including Tier 1 factors to the IPCC emission factor database (https://www.ipcc-nggip.iges.or.jp/EFDB/main.php). Inclusion in the database will enable researchers to include methodologies on CO_2 uptake in concrete in future updates of the IPCC guidelines.

[7] Andersson R., Fridh K., Stripple H. and Häglund M., Calculating CO_2 Uptake for Existing Concrete Structures during and after Service Life, Environmental Science & Technology, 2013, 47 (20), pp 11625–11633.

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