Natural carbon uptake in single-family homes: An element-level assessment approach

MIT CSHub Research Brief

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MIT CONCRETE SUSTAINABILITY HUB

Why model building-level carbon uptake?

Carbon uptake, the natural process by which **cement-based products** (CBPs) permanently sequester CO_2 from the atmosphere [i, 1], is an essential component of the life cycle impacts of CBPs.

The rate and extent of carbon uptake within a cement-based product (CBP) are influenced by several characteristics of... [2]

- The material:
  - Cement type (e.g., use of supplementary cementitious materials (SCMs))
  - Cement content
  - Concrete porosity
- The application:
  - Local climate
  - Exposure conditions
  - Geometry of the CBP

Due to the range of applications for CBPs and the variety of products on the market, a range of uptake results has been reported in the literature. In this way, it has become difficult to determine what a reasonable estimate is for a single-family home, or any type of building.

To address this gap, the MIT CSHub has developed a bottom-up, context-sensitive approach to estimate the carbon uptake of different CBPs in a building by estimating uptake in individual CBPs within that building [3]. This brief describes estimates for single-family homes and the elements they comprise derived using this modeling approach. These results are intended to help in making informed decisions about the capacities of CBPs in buildings to help (confine and) neutralize carbon emissions.

Key Takeaways

- Over the life cycle of a single-family home, carbon uptake (the natural binding of CO_2 in concrete and other cement-based products) sequesters 22-40% of the calcination emissions associated with producing the portland cement used in that home.
- The extent of natural carbon uptake can vary by a factor of ten among cement-based elements within the home.
- Natural carbon uptake is an important element of the life cycle impact of cement-based products but can also be considered a method for neutralizing CO_2 emissions.
- There are opportunities for designers, producers, and contractors to increase natural carbon uptake in many cement-based elements where prudent.

Key Results and their Utility

To understand the extent to which a single-family home's life cycle carbon uptake varies (depending on the element type and materials used for different parts of the building), we conducted carbon uptake estimates. The variables comprise a variation of basement or without basement and various materials for walls. As shown in **Figure 1**, the change in building compositions of a single-family home with a similar building size results in 1.07-3.03 tons of carbon uptake during its life cycle. From a sequestration percentage perspective, the use of dry-cast **concrete masonry units** (CMUs) in building walls increases the uptake sequestration percentage (right columns and bottom row). The relatively open structure of dry-cast concrete allows carbon dioxide to easily penetrate into the concrete. This in combination with the high surface-to-volume ratio of dry-cast CMUs and access to multiple exposure faces enable a fast carbon uptake of masonry blocks over the life cycle of buildings.

From the analyses of single family buildings, we found that the amount of uptake that took place in the dry-cast concrete masonry walls is an order of magnitude larger than the amount that occurred in the frame and footing. These walls fully carbonate within the first 20 years of the building's life. Slabs and footings, in contrast, partially carbonate during the building's life. Since the footings are buried beneath the ground, the carbonation rate is much slower, resulting in a lower total amount of carbon uptake than the concrete slab (45 kg CO2 uptake in the footing, 850 kg CO2 uptake in the slab over the life cycle of the single family building). In the concrete slab, the two surfaces are exposed to indoor (with cover) and inground conditions. We also observed that the structure's carbonation rate in general slows towards the end of service life. In fact, 70% of the total life cycle carbon uptake (use and end of life) happens before year 15 (**Figure 2** on the following page).

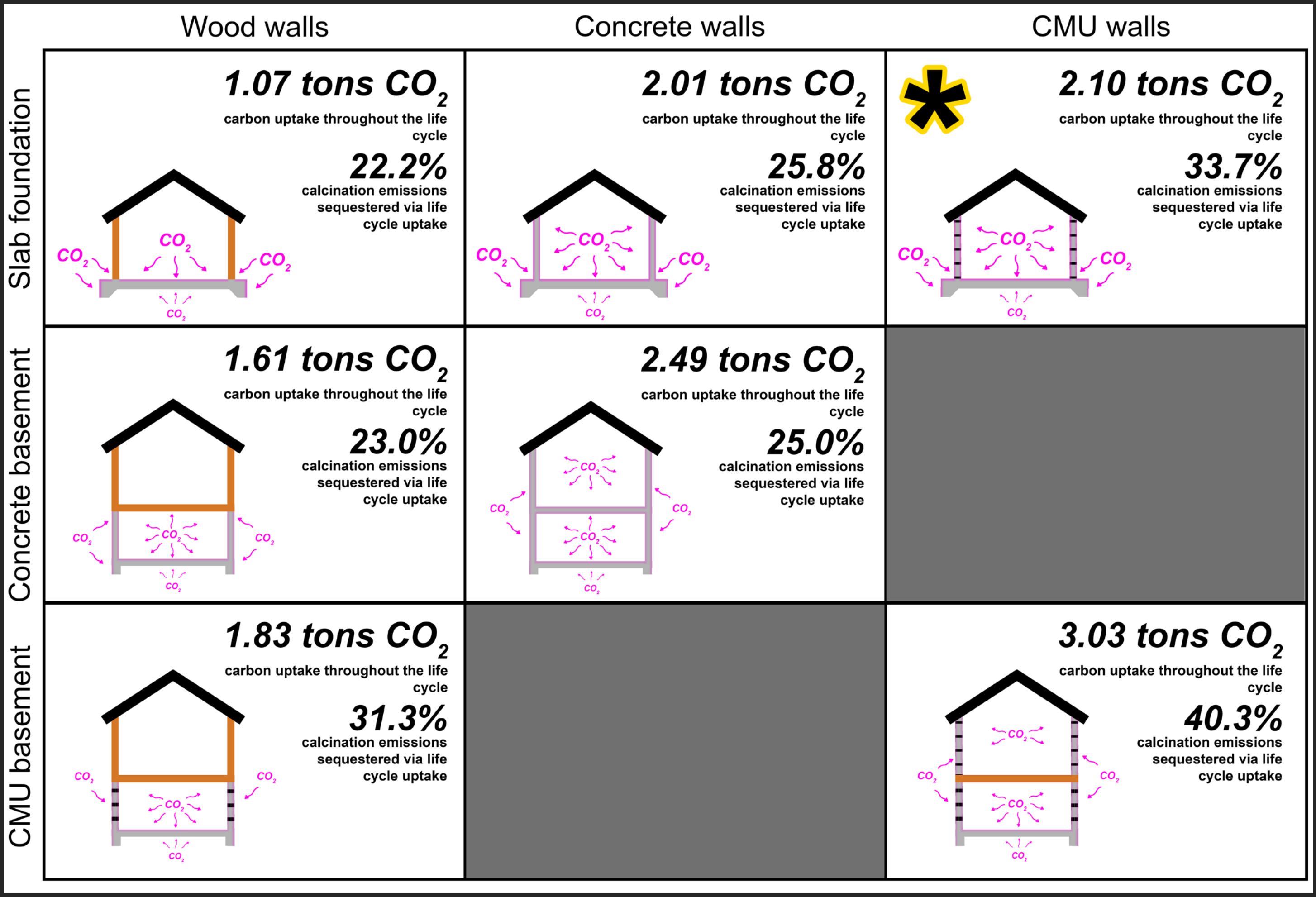

***Figure 1**: Life cycle carbon uptake of various configurations of single-family buildings and the percentage of calcination (process) emissions requested by life cycle carbon uptake.*

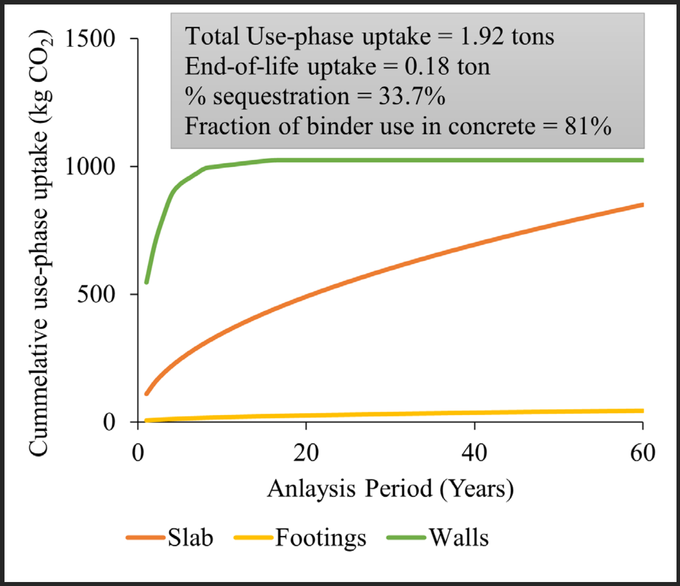

***Figure 2**: Cumulative use phase and end-of-life carbon uptake, the sequestered fraction of calcination emissions, and use-phase carbon uptake (curves) of cement-based products per floor area unit of a single-family U.S. residence archetype.*

The Role of Carbon Uptake in a Carbon-neutral Future

Our approach to estimating the carbon uptake of single-family residences shows the importance of considering the impact that each cement-based element of a structure has on the overall carbon footprint. Our findings have been used to develop the following recommendations for various stakeholders on how to leverage carbon uptake for carbon neutrality goals without compromising durability (**Figure 3 on the following page**). Both our results and approach could be implemented to estimate the carbon uptake of CBPs on regional scales. In this manner, key stakeholders and decision-makers can obtain a more accurate estimate of the role carbon uptake has to play in a carbon-neutral future. In addition, these estimations could be used to inform the design of cement-based structures that have a higher uptake potential, and therefore can more effectively reduce or neutralize the structures' carbon impact.

Ultimately, our estimate shows that the end-of-life carbon uptake is as large as 10% of the total life cycle uptake. This value can vary from one case to another depending on the use of dry-cast CMU products in buildings, recycled concrete aggregate grading size, exposure condition of recycled concrete, and landfilling time.

Modeling Methodology

The modeling framework estimates both the use phase and end-of-life uptake. We first developed an archetype of a typical single-family, U.S. residence with 232 square meters (2,500 square feet) of floor area and built using concrete with a mix composition defined based on the National Ready Mix Concrete Association's (NRMCA's) industry-average data [4]. The concrete mixture incorporates 215 kg/m^3 of portland cement, 37 kg/m^3 of slag, and 21 kg/m^3 of fly ash. We fixed the amount of portland cement for concrete masonry units (CMUs) as 185 kg/m^3 [5]. A table of the surface areas and corresponding exposure conditions for our U.S. single-family residence archetype is available in Appendix A.

We then estimated the cumulative use-phase uptake for this building over its service life by summing the uptake of each of its individual elements (e.g., slab, walls, etc.). This meant summing the uptake of each of the individual surfaces of each element, which is dependent on a carbonation rate, binder content, calcium oxide content of the binder, and **degree of carbonation** (the practical observed maximum uptake fraction, which is influenced by exposure condition). We obtained input data for carbonation rate and degree of carbonation from the EN 16757 standard [6]. For the use phase, we used an analysis period of 60 years, which is around the median percentiles of US residential buildings according to the U.S. Census Bureau data.

For estimating end-of-life uptake, we used the **MIT CSHub Whole Life Cycle Carbon Uptake tool** and assumed a six-month stockpiling period.

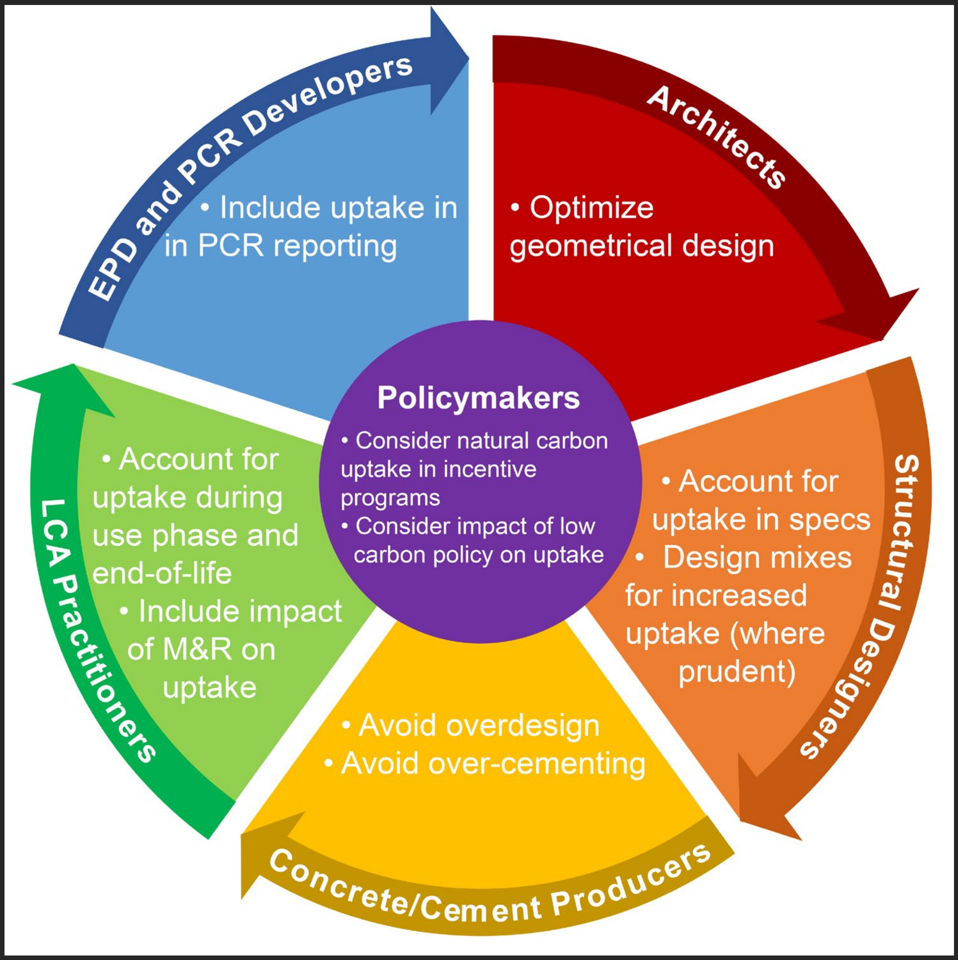

***Figure 3**. Natural carbon uptake is an engineered solution for reducing and neutralizing the concrete and cement industry's greenhouse gas emissions. Various stakeholders and policymakers across the value chain can leverage uptake to reach carbon neutrality goals. (**M&R** = Maintenance and Repair); (**PCR** = Product Category Rule).*

Appendix A

Element name	Surface area (m^2)	Exposure condition
Slab (floor of basement)	232.3	*Indoor, with cover & In ground*
Footing	52.4	*In ground*
Basement wall	175.3	*Indoor, no cover & In ground*
Building wall	129.8	*Indoor, with cover & Outdoor, with cover (sheltered from rain)*
Compressive strength (MPa)	15 – 20 MPa	

Table A1. Surface areas and corresponding exposure conditions for the U.S. single-family residence archetype (window-to-wall ratio of 0.3 was considered for two sides of the buildings).

Endnotes

[i] Carbon uptake, also referred to as **carbonation**, is the reaction between carbon dioxide and certain phases in hardened concrete and other CBPs that forms calcium carbonates. Uptake allows CBPs to permanently sequester carbon dioxide from the atmosphere. It occurs as a function of time during two phases of the CBP life cycle: the use phase (e.g., when a concrete building has been constructed and before it has been demolished) and the end-of-life phase (e.g., when concrete has been decommissioned and then demolished).

[ii] The following explanation from the news article cited in Reference [7] may be helpful in understanding the effects which mixture constituents may have on the uptake of CBPs: "The types and properties of cement-based products have a large influence on the rate of carbon uptake. For example, mortar (consisting of water, cement, and fine aggregates) carbonates two to four times faster than concrete (consisting of water, cement, and coarse and fine aggregates) because of its more porous structure. The carbon uptake rate of dry-cast concrete masonry units is higher than wet-cast for the same reason. In structural concrete, the process is made slower as mechanical properties are improved and the density of the hardened products' structure increases."

References

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