Interim Report:

Accounting for Carbon Uptake in the EPDs of Cement-based Products

Conceptual Framework

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Executive Summary

The natural mineralization of atmospheric CO_2 (i.e., **carbon uptake**) by **cement-based products** (CBPs) offers a mechanism for neutralizing a portion of their life cycle **greenhouse gas** (GHG) emissions. Over the last decade, **environmental product declarations** (EPDs) have provided a standardized framework for reporting and communicating the results of CBP life cycle assessments. Including carbon uptake in EPDs provides a more comprehensive understanding of the environmental performance of a CBP over its life cycle and will aid stakeholders in making informed decisions when choosing materials and design strategies.

Existing standards and reports provide guidelines to estimate the carbon uptake of CBPs. However, the methodologies outlined in these existing standards and reports are more general and do not incorporate user-level application-based input information. It is important to incorporate variability in input information as part of the carbon uptake estimation process since the degree of carbon uptake is sensitive to changes in environmental conditions and application-based factors (e.g., geometry and type of material used); further, there is currently limited data for certain factors that can drive carbon uptake, and as a result, modeling estimates have inherent uncertainty.

To address this gap, we propose an approach prescribing the carbon uptake of each concrete element based on a probabilistic framework to account for the variation and uncertainty associated with the input data.

In this report, a framework is proposed to account for carbon uptake in **Product Category Rules** (PCRs) for creating EPDs. The proposed method elaborates the multi-level approach adopted to define carbon uptake estimation based on the information available to EPD producers and users. The report highlights the need for a probabilistic framework to account for uncertainties associated with the input data and modeling approach. The report also aims to provide guidelines for producers to incorporate carbon uptake estimates into EPDs based on end-use applications and create a baseline for a science-based and transparent method generalizable to other components of a CBP's life cycle.

1. Introduction

Carbon uptake (also known as carbonation) is a natural phenomenon that provides an opportunity to neutralize[§] a portion of the greenhouse gas emissions associated with the manufacture of **cement-based products**[‡] (CBPs) when conducting **life cycle assessment** (LCA)[1]. The accurate estimation and reporting of carbon uptake as part of the LCA are critical components of the GHG footprint of CBPs and therefore must be recognized and quantified accurately. The long-term service life of concrete structures allows for the mineralization of CO_2 from the atmosphere over many decades[2]. To estimate the carbon uptake in CBPs, it is important to evaluate the environmental impacts associated with different stages of the life cycle, especially the use and end-of-life stages of the product[3]. Research on carbon uptake as a permanent and measurable CO_2 sequestration mechanism has been a focus area in past years. While certain technologies address engineered materials and methods to enhance carbon uptake by cement and CBPs during various stages of materials production, the focus of this document is on the natural carbon uptake of conventional CBPs such as ready-mix concrete during the use phase of the life cycle.

The incorporation of carbon uptake along with other pertinent components of the life cycle phases should be communicated to stakeholders in a clear and science-based manner in order to better describe the environmental impacts of products. The principles of transparency and comparability should be adhered to enable the standardization of these findings. The data intensity and lack of context-specific guidelines for calculating carbon uptake are the short-term major barriers to adopting carbon uptake as a part of the life cycle environmental impact of CBPs. In this report, we describe how to overcome these barriers by implementing a multi-level framework, leveraging accurate and reliable data, and accounting for uncertainties and variations inherent in carbon uptake estimation.

[§] Cement Science Based Target Setting Guidance (SBTi, 2022) by Science Based Targets initiative describes natural cement recarbonation as a process to neutralize the residual emissions of the cement industry.

[‡] Cement -based products include the mixture of hydraulic cement, (fine and/or coarse) aggregates, and water, with or without admixtures, fibers, or other cementitious materials.

2. Carbon Uptake Mechanism and Impact on Cement-based Products

Accounting for the natural carbon uptake in cement-based products (CBPs) over the lifetime of built environment elements (e.g., buildings, concrete pavements, etc.) has been reported as an important carbon sink measure by the Intergovernmental Panel on Climate Change (IPCC)[4]. The reaction of carbon dioxide in the atmosphere with the calcium-rich products (from cement hydration) in the CBP binder results in the formation of various forms of calcium carbonates[3]. As a result, CBPs slowly sequester CO_2 over their service life. The intensity and extent of carbon uptake in CBPs depend on the four major factors below:

1. *Climate and exposure conditions:* Carbon uptake occurs when the CBP is exposed to atmospheric CO_2 and the rate of carbon uptake depends on the CO_2 concentration in the surrounding air. The extent of local CO_2 concentration is influenced by factors such as location (urban vs. rural), proximity to industrial sources, and ventilation. Environmental factors such as temperature, humidity, and exposure to moisture affect the rate and extent of carbon uptake[5]. Higher temperatures generally accelerate the carbon uptake process, and (moderate) moisture availability facilitates CO_2 transportation within the pores of CBPs [6]. While lower moisture may enhance CO_2 diffusion, it limits the carbon uptake process due to insufficient moisture for chemical reactions.
2. *Type and properties of CBPs:* Porous CBPs with high permeability can allow for greater ingress of CO_2, causing a faster rate of carbon uptake[7]. Carbon uptake rates are impacted by the permeability and porosity of CBPs, characteristics which are influenced by factors such as water-to-binder ratio and curing conditions, among others.
3. *Binder system:* Carbon uptake is influenced by the composition of the CBP. Products with a relatively high portland cement content (and lower **supplementary cementitious materials** (SCMs) content) and equivalent water to cement ratios will typically exhibit slower carbon uptake rates compared to the mixtures with SCMs. Although SCMs generally decrease the potential for carbon uptake relative to cement clinker, the presence of SCMs may accelerate the carbon uptake rate (mm/year$^{0.5}$) depending on the type and quantity within the binder system[8].
4. *Geometry:* Carbon uptake primarily occurs at the surface of the CBP, where CO_2 can readily diffuse into the porous material. Increased exposed surface area-to-volume ratio enhances carbon uptake rates per unit mass or volume by providing more area for the sequestration of CO_2[9]. Surface treatments such as coatings or sealers may reduce the carbon uptake potential.

The impacts of carbon uptake on the hardened properties of CBPs are notable and well-studied. The impacts of carbon uptake on CBPs, specifically concrete, are outlined on the next page. Due to these factors, it is important to identify and understand the interaction between the microstructure of a CBP and the carbon uptake chemical process involved to effectively evaluate the impact of carbon uptake on the performance of CBPs.

1. *Potential for steel corrosion in reinforced elements:* The process of carbon uptake of concrete reduces the pH of the pore solution[10]. This drop in pH weakens the passive layer that is protecting the reinforcing steel, which can lead to corrosion initiation. As steel corrodes, it expands, putting pressure on the concrete from the inside, which can lead to cracks as a result of tensile strength failure to resist the pressure; this mechanism is commonly known as a deterioration mechanism of reinforced concrete[11,12]. Although the carbon uptake process is typically slow, the susceptibility of steel reinforcement to corrosion is dependent on the environmental conditions (humidity, temperature, etc.), porosity of the concrete, as well as the cover provided—factors which are considered by the structural engineer while designing the concrete element. Increased cover and use of non-metallic reinforcement can help mitigate corrosion. However, it is important to not overlook the structural integrity and safety factors while considering carbon uptake.
2. *Variation in strength of concrete:* The strength of the concrete that is carbonated during the carbon uptake process is impacted by various factors including the quantity and type of SCMs in the binder. The mechanism of carbon uptake in SCM-incorporated mixtures varies from that of ordinary portland cement mixtures[8]. In mixtures with a low SCM content—where the portlandite (calcium hydroxide) content is relatively available at larger quantity—the formation of calcium carbonates may contribute to improved strength over time. On the other hand, mixtures with a high SCM content (e.g., slag incorporated) may be observed to have a decrease in strength as a result of the carbonation process.
3. *Shrinkage:* Additional shrinkage may occur due to carbon uptake. This can be driven by the decalcification of calcium silicate hydrates that occurs during the carbon uptake process[13] or the formation of calcium carbonate during the chemical process of carbon uptake[12].

3. Challenges and Issues of Incorporating Carbon Uptake in EPDs

An accurate estimate of carbon uptake in cement-based products (CBPs) can provide a more comprehensive picture of CBPs' life cycle GHG emissions. Over the past decade, the cement and CBP industries have dedicated considerable effort to reporting the environmental impacts of CBPs using environmental product declarations (EPDs). EPDs are standardized and independently verified documents created by the CBP manufacturer or producer. The information in EPDs communicate the potential environmental impacts (e.g., GHG emissions) associated with the processes during a given product life cycle[14]. Currently, most of the CBP EPDs in the United States are developed with a **cradle-to-gate scope** (scope A1-A3), which includes the potential environmental impacts calculated from initial material production (e.g., extraction of raw materials) up to the gate of the production location. This is because the system boundary covered in the product category rule (PCR) of CBPs used in North America have provisions for only A1-A3 and no provisions for rest of the life cycle stages. As a result, the impact of carbon uptake is generally excluded in the current CBP EPDs.[5] In contrast, EPDs of other types of construction materials such as bio-based products include the potential of biogenic carbon sequestration and release throughout the life cycle [15].

The **British/European Standard BS EN 16757**[16] provides a simplified methodology to compute carbon uptake in concrete. While this methodology incorporates the research outcomes of multiple universities over the past few decades[5,17,18], the outlined procedure may need to be further refined to incorporate context-specific inputs. As mentioned earlier, carbon uptake is impacted by environmental conditions, climate, and construction practices. It is known that climate factors and variations substantially change the rate and degree of carbon uptake.

The EN standard approach also provides a simplified methodology for assessing carbon uptake when the final application of concrete and its properties are not fully specified. The method and underlying data (collected from the IVL report[3]) are reported deterministically and do not include data variability.

The probabilistic evaluation of carbon uptake provides the potential range for carbon uptake considering different levels of data availability. The proposed framework can enable users to calculate the uptake depending on the known information about the project and the type of element that will be produced with a CBP, while retaining a conservative approach when certain information is unknown. Carbon uptake may also be impacted by construction and design practices. The design and construction codes and practices vary significantly from one region to another. When considering carbon uptake estimation at the structure and element levels, the thickness and hardened properties requirements of CBPs vary significantly. Therefore, in the absence of detailed information on the designated cement-based elements (i.e., the case where a simplified methodology is to be used), the representativeness of construction practices plays a major role in the accuracy of carbon uptake estimation.

A probabilistic approach to account for data variability and uncertainty minimization would improve the existing approach for including carbon uptake in EPDs.

Incorporating carbon uptake in EPDs is a major step toward a comprehensive impact assessment of cement-based products. In the MIT CSHub framework, a multi-level approach for estimating carbon uptake in cement-based products is proposed to enable stakeholders to include carbon uptake in EPDs based on any level of data accessibility. This is the first attempt to provide specific, transparent, and science-based guidelines to include activities beyond the gate to EPDs for CBPs. The conceptual framework discussed in this report can be extended to other components of the construction, use, and end-of-life phases of cement-based products.

4. Objectives

The primary goal of the report is to develop a conceptual framework that can be used by Product Category Rules (PCR) for EPDs of cement-based products (CBPs) to account for carbon uptake. The key objectives of this report are to (**a**) Develop a multi-level framework based on the granularity of input data available to end users (i.e., the stakeholders who use EPDs for decision-making), (**b**) Develop guidelines for producers to include end-use application-based information in EPDs that can facilitate the transfer of information required to estimate carbon uptake, (**c**) Incorporate a probabilistic framework to account for the associated uncertainties in carbon uptake estimation, and (**d**) Provide instructions on the minimum level of data requirement for robust estimation of carbon uptake. The initial focus of this report is on natural carbon uptake estimation during the use phase. The methodologies developed for this initial task will then be applied to estimate the end-of-life carbon uptake in CBPs.

5. Proposed Framework for Incorporating Carbon Uptake in Cement-based Product EPDs

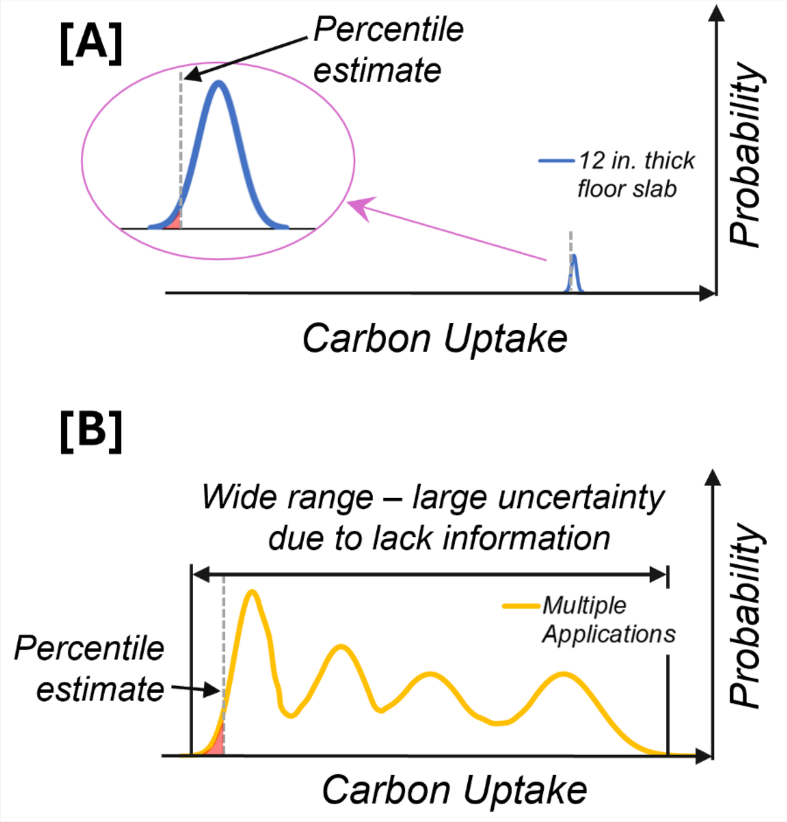

***Figure 1**: Distribution of carbon uptake values for a cement mix going into **[A]** a fully specified element (a particular application with known geometrical parameters such as a 12-in thick floor slab of an office building with known exposure conditions) and **[B]** a wide variety of applications. An estimate (grey dashed line) based on a low non-exceedance probability (shaded region) could be relatively inaccurate in case [B] due to the wide range of carbon uptake values obtained from the multiple applications for which the CBP is used.*

While there are advantages to including carbon uptake information for CBPs in EPDs, the challenge that most producers are facing is how to estimate the use and end-of-life carbon uptake in a usable format. Producers develop EPDs to increase transparency and communication about the potential environmental impacts of CBPs. However, the information for carbon uptake estimation from a producer perspective is generally limited to the mixture compositions and mechanical properties. Other required inputs (e.g., climate conditions, exposure condition and element geometry) are dependent on the subsequent application of the CBP. As shown in **Figure 1[A]** above, if the end-use application of a CBP is known (e.g., a 12 in. thick floor slab of an office building), a distribution of carbon uptake values (blue solid curve) may be obtained from which a percentile value (grey dashed line) may be reported. However, this information may not be available at the early stages of the procurement process. Therefore, the challenge in estimating carbon uptake that the producers—and to some extent, users— are facing is accounting for the wide variety of CBP end-use applications such as buildings, pavements, and other infrastructure. In this sense, the variety of applications poses the challenge of creating considerable uncertainty in computing the appropriate carbon uptake associated with an application. A percentile estimate reported from this distribution could be extremely different in nature as shown in **Figure 1[B]** above.

Carbon uptake may vary considerably for a given product, translating into significant uncertainty that cannot be interpreted into an accurate estimate for decision making. This large uncertainty arises from the magnitude of unknown information on multiple important parameters that impact carbon uptake. Reporting a carbon uptake value, a conservative estimate (marked using the grey dashed lines in **Figure 1[B]**) based on a low non-exceedance probability, with only the material compositions and mechanical properties information could overall be too uncertain to be useful.

To address this high risk of uncertainty at a material level, we propose viewing this issue as a two-stage process (as shown in **Figure 2**): the production or producer stage and the end-use or user stage. First, at the producer stage, information related to the compositions such as the binder content, type of cement, and compressive strength (parameters that affect the rate of carbonation and maximum carbon uptake potential) are typically available and will be collected for estimating the carbon uptake. At the second stage, the downstream user level, some or all of the information related to the end-use application, location, and geometric details could be more accurately ascertained. Also, concrete manufacturing digitization has enabled producers to collect and store the data relevant to the end-use application of the CBPs. In this sense, the end-use application data may already be stored in the producer database. The complementary data sources from the producers and users ensure that EPDs can bridge this gap and facilitate a more accurate carbon uptake estimation.

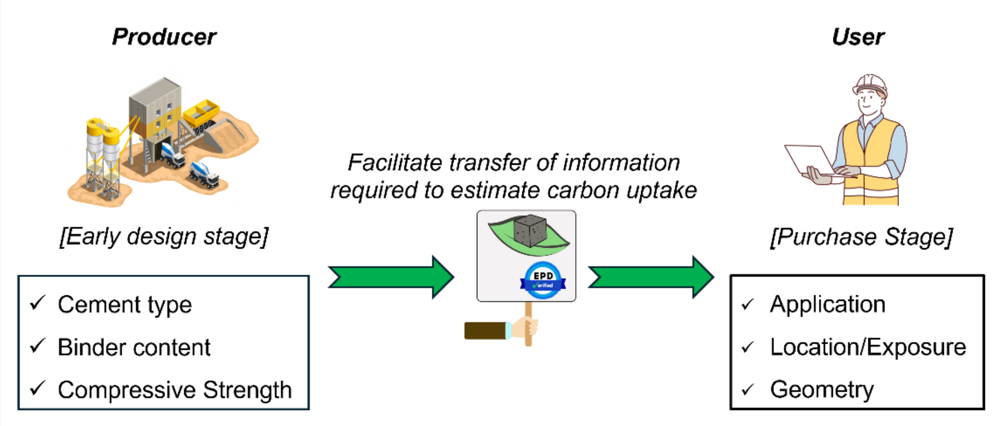

***Figure 2**: The two stages along with the set of information that is typically available at each stage that are required to systematically compute carbon uptake.*

End-use applications of CBPs may broadly be divided into buildings, pavements, and other infrastructure. Since the estimation of carbon uptake using only producer-level data is highly uncertain for any beneficial use, it is proposed to focus on the carbon uptake computation using user-level data. Typically, producers are aware of the different types of applications into which the developed mix will be fashioned. The available information from the user — depending on their position in the supply chain (e.g., contractor, private or public owner, etc.) — can be further divided into different levels with varying degrees of information and details.

6. Explanation of the Proposed Framework for Ready Mixed Concrete EPDs

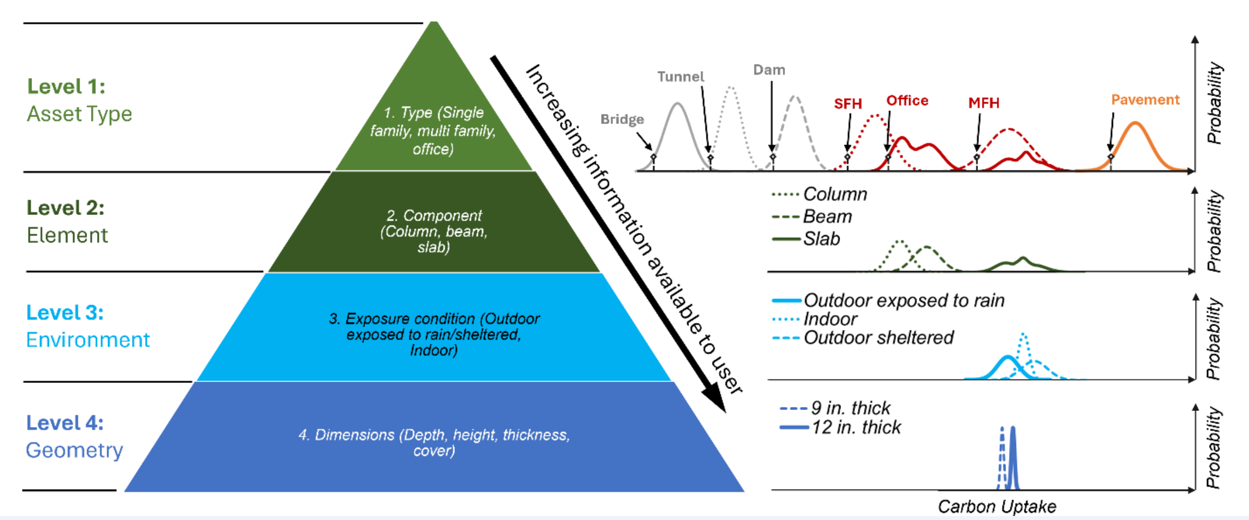

Figure 3*: Proposed probabilistic framework to estimate carbon uptake using end-use information. (Left) Proposed pyramid with the bottommost level (Level 4) has the most granular information available to the user/producer. (Right) A schematic representation of the probability distribution curves of different components at each level.*

To demonstrate the structure of our proposed framework with specific detail and examples, we focus on the ready mixed concrete applications. However, the framework is generalized and therefore can accommodate any carbonation model and can be expanded to other cement-based products (CBPs) with further adjustment on the end-use applications.

Figure 3 presents the proposed framework to estimate the carbon uptake potential of ready-mixed concrete applications. **Figure 3** (left) shows the proposed multi-level approach with Levels 1 to 4 representing the potential range (in terms of completeness) of available context information. As the first level of information availability, only the asset type will be specified. For example, if the use of concrete mix is for a building application, the first level of information will be to identify which type of building is considered (e.g., single-family residential building, multifamily residential building, commercial building, etc.). Specifying the application in more detail is attained at the second level where the type of component in that application (e.g., column, foundation, beam, or slab of a building) is known. This level of information at the user end provides more accuracy in terms of surface-to-volume ratio compared to the previous level, however, it still does not provide all the information. Since the carbon uptake rate largely depends on the environmental and climatic conditions, information about the exact exposure conditions of the component is needed for determining the carbon uptake with higher accuracy and this forms the third level of the pyramid. The fourth and final level of end-user information provides the maximum details of the concrete product specifying the dimensions of the component such as the depth, height, thickness, and the concrete cover to steel reinforcement to determine the potential carbon uptake with the least uncertainty.

Figure 3 (right) shows a schematic representation of the probability distribution curves associated with each level. As shown from top to bottom, with the availability of each level of user-specific information, the degree of uncertainty (range of distribution) decreases. Therefore, this schematic illustrates the importance of user-furnished data for reducing uncertainty.

At the highest level, Level 1, the distributions for different asset types show a spread in carbon uptake values with high uncertainty for each asset type utilizing a particular concrete mixture. For example, the solid maroon curve shows a wide range of carbon uptake values that may be obtained for office buildings with insufficient information regarding the component and geometric details. These distributions may be computed with sufficient end-use application data and a representative carbon uptake value may be selected for each type at a certain point on the distribution curve, usually at the lower percentile of the curve with a reasonable level of exceedance probability. This uptake value may be reported in the EPD as a representative estimate for each asset application type. At Level 2, with the information regarding the component type known in addition to the asset type details, the uncertainty and variability associated with carbon uptake are reduced. For instance, the distributions corresponding to Level 2 represent the concrete components such as columns, beams, and slabs of an office building where the range of uptake values of each component is smaller compared to the range of values for an office building. At Level 3, with known exposure conditions, distributions for different exposure conditions provide carbon uptake with lower variation. As an example, the distributions corresponding to Level 3 represent the uncertainty ranges associated with different exposure conditions to which the slab components of an office building may be exposed. Clearly, the width of the distributions narrows down showing how the range of uptake values reduces as compared to the component level (Level 2). At the bottommost level, Level 4, it is shown that with the availability of geometric parameters, the carbon uptake value is nearly accurate with a small variation. For example, the solid blue line, representing a 12-inch thick floor slab exposed to outdoor conditions, shows an accurate carbon uptake value with small uncertainty.

Therefore, the strategy proposed herein is to define multiple scenarios based on the asset application type and provide tables and/or charts with carbon uptake values for each mix design in the EPDs as schematically shown in **Figure 4** on the following page. In the example chart shown in **Figure 4**, different asset types represent different application scenarios such as buildings, (including but not limited to three types shown in the example), pavements, and other infrastructure. This will help the end-user access to the first order of estimate for the carbon uptake. Depending upon the granularity of the end-use application detail available, the producer can report a reasonable number of scenarios for lower levels as well, for example, a cement-based floor slab (Level 2) or a bridge girder exposed to an outdoor environment but sheltered from rain (Level 3). However, reporting Level 2 and Level 3 would be optional. A structured end-use application-based carbon uptake analysis and uncertainty quantification are to be conducted to understand the scale and number of scenarios required for including the Level 2 and 3 information. Although reporting the data for all

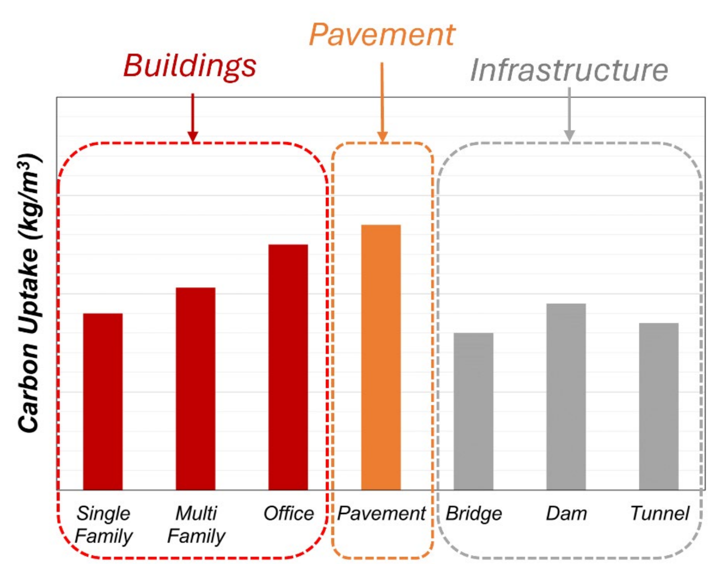

***Figure 4**: A graphical template of application scenario-based representative carbon uptake estimate for a concrete mix for reporting in an EPD.*

applications for different mix designs may seem tedious due to the number of scenarios, it should be noted that each mix design corresponds to certain types of applications, thereby condensing the number of scenarios considerably. However, reporting Level 4 carbon uptake values is complex due to the vast number of scenarios possible and therefore, it may be useful to use a tool that could handle the high level of complexity involved at Level 4.

An example of a building application is used in **Figure 5** below to illustrate the hierarchy of input parameters at different levels explained earlier. The asset type determined at Level 1 can be broadly classified as residential or nonresidential (commercial) buildings. The residential buildings can be further subdivided into single-family and multi-family units while the non-residential building sector would include offices, warehouses, educational,

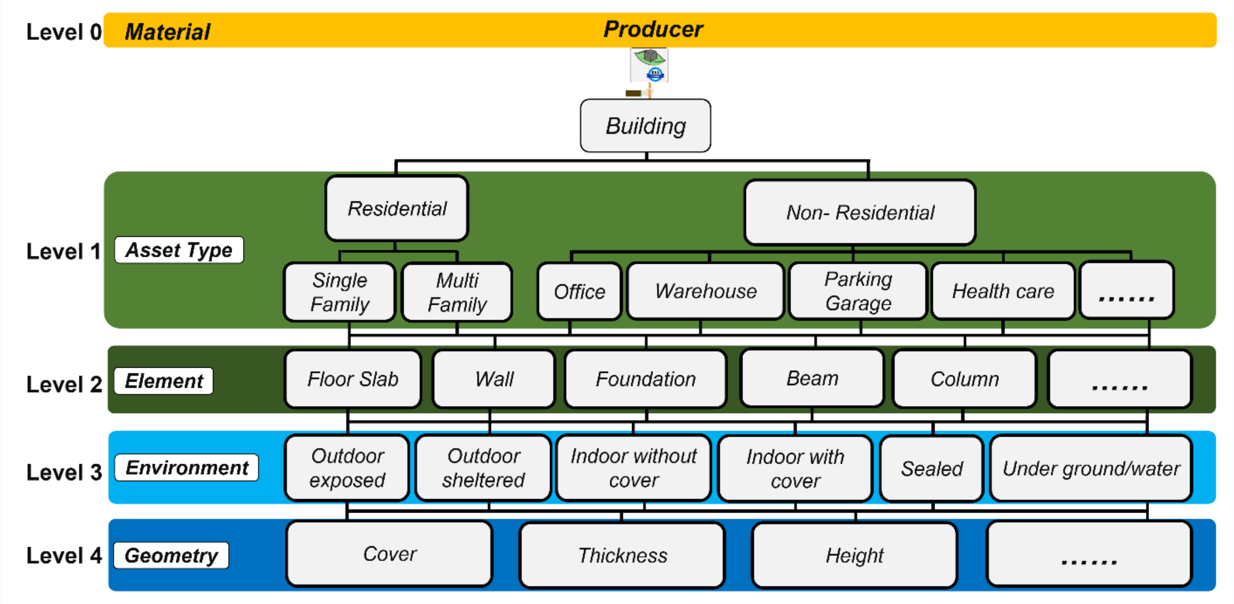

***Figure 5**: A schematic overview of the hierarchy of input parameters at different levels for building applications.*

hospitality, and healthcare facilities. This level has the highest uncertainty in predicting the carbon uptake estimates. Level 2 can be further streamlined by identifying the elements of each of the asset types being considered. This may include concrete components such as floor slabs, beams, columns, walls, foundation/footings (buried elements), and facades. At Level 3, each of these components may be exposed to different environmental and climatic conditions. These exposure conditions may be broadly classified as outdoor exposed or sheltered to rain, indoor with or without cover, sealed using sealers or coatings, buried underground, and submerged underwater. These exposure conditions directly impact the rate and degree of carbon uptake and thus the total carbon uptake of concrete. The fourth and final level includes geometric parameters such as depth, thickness or height of the component under consideration.

A systematic approach may be adopted to perform the carbon uptake calculation using the hierarchy of input parameters described above. The first step here is to identify all the key components associated with each level for the respective end-use application upon discussion with experts on the subject matter. The next step is to develop a database to compile all the input data for each component from different reports, articles, databases, inventories, and standard specifications going from Level 1 down to Level 4. Reasonable assumptions may be made where appropriate input data is not available. This is followed by carbon uptake calculation and uncertainty quantification for different categories and components using the respective input information. Depending on the applicable category at Levels 1 through 3, a different hierarchical chain is followed for the respective geometrical parameters.

7. Broader Impact and Concluding Remarks

This report proposes the conceptual framework of a multi-level approach for incorporating carbon uptake in cement-based product EPDs. A uniform methodology for computing the carbon uptake potential using equations for different levels is proposed to be used to provide consistent guidelines for the EPD development process such that there is flexibility for input variables at different levels. The consistency of this methodology would facilitate its use over a wider range of climatically diverse regions and applications. These advantages may help the PCR committee standardize the introduction of carbon uptake data in EPD reports of concrete products.

Though data extraction becomes more cumbersome as the levels become more specific, the accuracy of the computation increases. A trade-off between the data procurement and reduction in uncertainty of computation of carbon uptake exists at each level of the proposed pyramid. Such an addition to EPDs will be a step forward in assessing the environmental impacts of cement-based products (CBPs) more holistically. We envision that the generation of a transparent methodology and underlying data and assumptions yield meaningful information on carbon uptake and will help with the standardization of carbon uptake in EPDs and encourage more sustainable product development.

Previous standards such as the British/Eurocode standard BS EN 16757:2022 incorporate carbon uptake and there is a need for carbon uptake to be incorporated in other regional

PCR for CBPs. However, the approach adopted by Eurocode does not fully capture the context and account for the uncertainty involved and there is a need for probabilistic handling of the carbon uptake computation across different levels of user-supplied information and data.

Equipped with the potential carbon update across various application scenarios for a given concrete mix, the user will be able to account for carbon uptake when identifying sustainable products for a given end-use. This process may also result in the market being more proactive about optimizing the products and design to be more sustainable. With the probabilistic quantification of carbon uptake and accounting for uncertainty, it may pave the way for more stringent requirements for the construction industry to opt for sustainably accountable construction practices and products. The data generated and organized for this effort will benefit both the producers and users to get a better understanding of the carbon uptake and the stakeholders may find that more transparent information on carbon uptake in CBPs helps them conduct more accurate carbon accounting of embodied carbon in buildings and infrastructure and helps inform product selection.

8. Next Steps

1. The proposed framework accounts for only the use phase carbon uptake calculation. This method should be expanded to include the calculation of end-of-life carbon uptake.
2. The framework proposed in this report may be limited to ready-mix concrete applications at the time of publication because of input data availability. Steps need to be taken to extend this framework for other concrete products such as concrete masonry units (CMUs), precast concrete, etc.
3. The components and details of each level of hierarchy for different applications will be determined and reviewed after discussion with subject-matter experts.
4. Depending on the number of scenarios defined at the most-detailed level, a tool will be developed to perform Level 1 to Level 4 carbon uptake calculations.

9. Acknowledgement

This development of this framework was conducted as part of the Concrete Sustainability Hub at the Massachusetts Institute of Technology, which is supported by the Concrete Advancement Foundation.

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