Towards Accurate End-of-Life Carbon Uptake Modeling:

Impacts of Crushed Concrete Grading on Cement Paste Content and Degree of Carbonation

MIT CSHub Research Brief
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MIT CONCRETE SUSTAINABILITY HUB

What is end-of-life carbon uptake in crushed concrete and why is it important?

Concrete structures, upon demolition, generate large volumes of crushed concrete, which are often recycled or reused in construction to promote sustainability and circularity [1]. In addition to avoiding the use of newly mined aggregates, crushed concrete can sequester CO_2 through carbonation reactions [2]. **End-of-life (EOL) carbon uptake refers to the amount of atmospheric CO_2 sequestered by crushed concrete after demolition** [3]. This process can continue for years as long as the material remains exposed to humidity and CO_2. Accurately modeling EOL uptake is crucial to comprehensively assessing the life cycle environmental impacts of concrete.

Need for an improved and refined end-of-life carbon uptake model

The development of an accurate EOL uptake model is hindered by a lack of detailed experimental data, especially concerning the influence of the size distribution of aggregates in a crushed concrete sample (**grading**), and the amount of cement paste on that sample (**paste content**). The paste content is a key determinant for EOL uptake, and its distribution varies widely with crushed concrete grading [4]. Similarly, carbonation rates are not uniform across crushed concrete gradings; finer aggregate particles generally show a higher carbonation rate due to greater surface area and paste content [4]. Figure 1 shows the grading of typical crushed concrete, where ~50% of the material is within the fine fraction (0–4 mm). Therefore, this brief describes the development of a refined model of carbon uptake that considers grading and paste content.

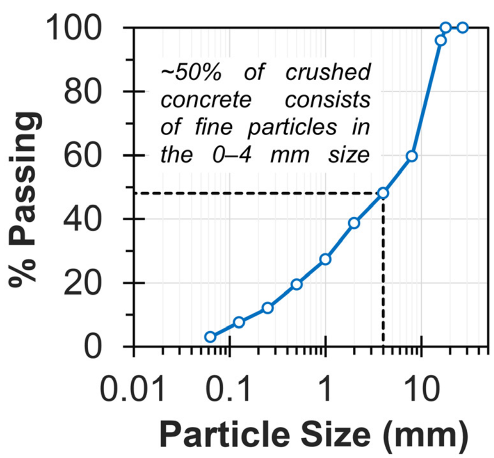

Figure 1: Grading of typical crushed concrete. The distribution shows that nearly half of the crushed concrete material falls within the fine fraction (0–4 mm). Therefore, it is essential that modeling accurately captures the role of grading on carbon uptake. (Note: Data from Stripple (2013) [4].)

Key Takeaways:

- Fine crushed concrete particles exhibit ~270% higher paste content and ~36% higher degree of carbonation[i] compared to coarse crushed concrete.
- Existing models for carbon uptake in crushed concrete overlook the carbon uptake of fine gradings.
- ~33% higher uptake was observed compared to the results obtained using the existing model on a representative crushed concrete sample.

Demolished concrete structures generate large volumes of crushed concrete, which are often reused or recycled in new construction as part of a circular economy. Due to the large surface area to volume ratio of crushed concrete, it can sequester a significant amount of atmospheric carbon dioxide. The CSHub has developed a model examining the impacts of crushed concrete grading on cement paste content and degree of carbonation.

Image Source: Washington State Department of Ecology

Proposed model: Integrating grading effects

This model improves accuracy by linking grading to two primary drivers of EOL uptake in crushed concrete: residual cement paste content and degree of carbonation. The model is built from data reported in the literature [5] and from additional experimental measurements.

Figure 2 illustrates the relationship between paste content and grading. In addition to the observed data, Figure 2 shows a fitted curve and confidence intervals corresponding to ±1 and ±2 standard deviations. The model displays strong alignment with the observed variation in paste content. This functional form provides a flexible and scalable model that can be used to estimate paste content for any arbitrary particle size, eliminating the need to categorize crushed concrete into fixed size classes and improving the reliability of uptake calculations. From this data, we observe that, on average, the finer particles (0-4 mm) contain ~270% more paste than the coarser particles (8-16 mm).

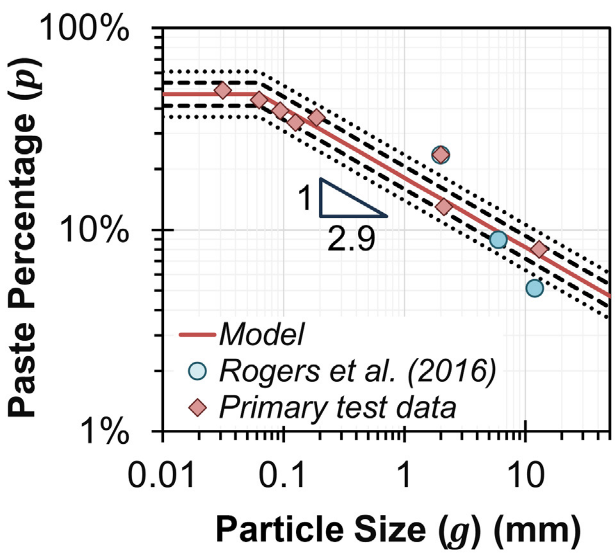

Figure 2: Paste content is crushed concrete as a function of particle size (Note: The values on x- and y- axis are presented on log-scale).

The second component of the model estimates the degree of carbonation, which quantifies the fraction of available paste that has reacted with CO_2. Figure 3 presents the proposed degree of carbonation model as a function of crushed concrete particle size. In general, the degree of carbonation is highest in the finest particles due to high surface accessibility and fast carbonation rate. For coarser fractions, the degree of carbonation is limited to the outer layers, leading to reduced overall carbonation. Finer particles show, on average, a degree of carbonation that is 36% higher than that of coarser particles.

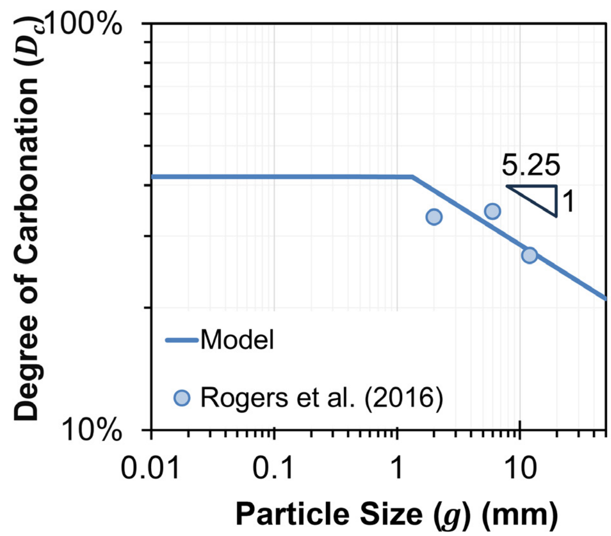

Figure 3: Proposed grading based degree of carbonation model. (Note: The values on the x- and y- axes are presented on log-scale.)

Implementation of the proposed model to calculate the EOL carbon uptake of crushed concrete

The proposed grading based models for paste content and degree of carbonation were applied to a representative crushed concrete material (shown in Figure 1). The proposed model was used to estimate the EOL carbon uptake across the full grading of the sample material as depicted by the maroon markers in Figure 4. Figure 4[A] shows the paste content model where the paste is capped at 47% for particles less than 63 μm and decreases with increase in grading following a power law relationship as shown in Figure 2.

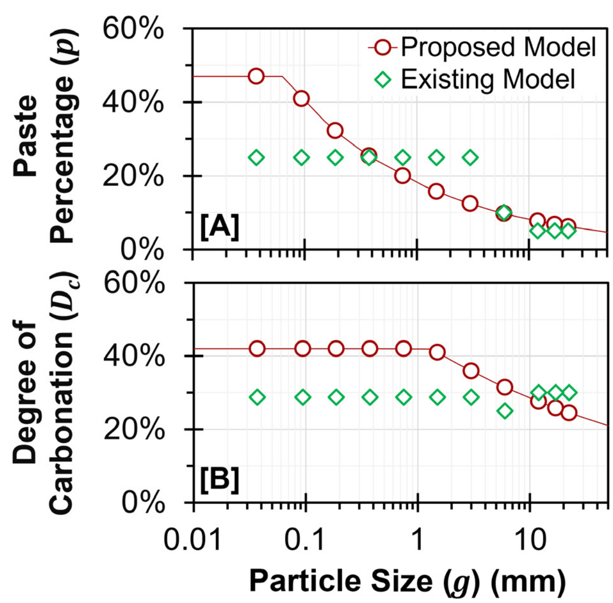

Figure 4: Comparison of paste content and degree of carbonation for a representative crushed concrete (shown in Figure 1) using the proposed grading based model (maroon markers) and existing model (green markers). (Note: The values on the x-axes are presented on log-scale.)

The degree of carbonation model accounts for limited airflow and restricted CO_2 diffusion in finer particles, capping the degree of carbonation at 42% for particles less than 1.18 mm (as shown in Figure 4[B]), and is based on a combined outer and inner layer reactivity observed in the literature [5, 6]. For particles larger than 1.18 mm, the degree of carbonation decreases with an increase in grading following a power law relationship, as shown in Figure 3. Given the limited data availability, the current degree of carbonation model adopts a conservative approach. However, the model is designed to allow future refinements as additional measurements become available through further research by which the accuracy of both the model and the resulting EOL carbon uptake calculations can be improved.

Based on the proposed models, the total EOL CO_2 uptake of the crushed concrete sample is estimated to be ~39 kg CO_2 per m^3 after 1 year. In comparison, the same analysis was performed using the existing model from Stripple et al. (2021) [6] that assumes fixed values for paste content and degree of carbonation across gradings within a defined size fraction as shown by the green markers in Figure 4. The Stripple model yielded a lower uptake of ~29 kg CO_2 per m^3 after 1 year.

These findings demonstrate that the proposed model results in ~33% increase in the estimated EOL carbon uptake, underscoring the importance of incorporating grading specific variability into carbon uptake assessments. Specifically, the model captures the higher carbon uptake of finer crushed concrete fractions while appropriately estimating the uptake in coarser particles. By more accurately capturing the paste content and degree of carbonation of fine crushed concrete fractions, which constitute a substantial portion of the material distribution (~50%), the refined model offers improved accuracy and reliability for carbon accounting.

Acknowledgment

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Endnotes

[i] Degree of carbonation is defined as the ratio of the carbonated calcium to the total calcium in the residual cement paste of crushed concrete. It reflects the actual conversion of reactive calcium to carbonate over time under atmospheric conditions.

References

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Related Links

[i] MIT News, March 2023: “3 Questions: Leveraging carbon uptake to lower concrete’s carbon footprint”

[ii] MIT CSHub Research Brief, July 2024: “Natural carbon uptake in single-family homes: An element-level assessment approach”

Citation

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