# Solutions for Net-zero Carbon Concrete in U.S. Pavements

CSHub Research Brief | Volume 2021, Issue 5 | Hessam AzariJafari | hessam@mit.edu

MIT CONCRETE SUSTAINABILITY HUB

## Low-carbon Concrete in Context

The contribution of concrete's embodied impacts to global greenhouse gas (GHG) emissions has received increased attention in recent years. This is particularly the case with concrete pavements, the main consumer of cement after buildings. While it is always important to place concrete's embodied emissions in the material's broader life cycle, addressing these emissions is crucial to reaching the goal of net-zero* concrete. To help guide decarbonization, this brief outlines the various strategies needed to reduce and offset the embodied impacts of concrete in the U.S. pavement network.

The adaptability of concrete as a composite material allows for numerous possible GHG reduction solutions. Realizing all of these solutions—which address the design stage, the concrete supply chain, and end-of-life management—will require continued research and significant public and private sector investments. The effectiveness of some solutions, for instance, is limited by current prescriptive engineering standards. This brief will explain these different constraints as well as present frameworks for the implementation of lower-carbon concrete pavements—including one framework that demonstrates a pathway to net-zero emissions in 2050.

## Key Takeaways:

- Concrete mixtures with zero embodied carbon can be attained using the simultaneous benefits of reduction, replacement, reuse, recycling, and $CO_2$ sequestration solutions.
- Compared to the 2017 GHG emissions level, alternative cements and carbon capture strategies can mitigate around 60% of GHG emissions by 2050.
- Technical and economical barriers, as well as market acceptance, should be considered in future work to investigate the feasibility of these solutions in different regions.

* In the context of this brief, 'net-zero' and 'carbon-neutral,' refer to the same concept: when emissions are entirely offset and/or reduced by various means.

## Modeling Emissions Reductions

In this work, researchers estimated the future demand for concrete pavements between 2017 and 2050 using data analytics and regional practices and then predicted the corresponding embodied impacts of those pavements. The scope of this analysis represents the entire U.S. pavement sector with important differentiation at the state level. The embodied impacts considered include the GHG emissions from the supply chain of construction materials production for both maintenance and repair as well as for reconstruction. The implementation of these treatments in the network aligns with the typical budgets in each state.

After building this model, researchers then defined and implemented various GHG reduction solutions for supplying future concrete demand in the pavement sector (**Table 1**). These solutions were examined through two perspectives: their (1) feasibility and (2) implementation.

The first perspective (**Figure 1**) shows how an ambitious emissions reduction scenario (**Table 1**) could feasibly achieve net-zero emissions in 2050 through a

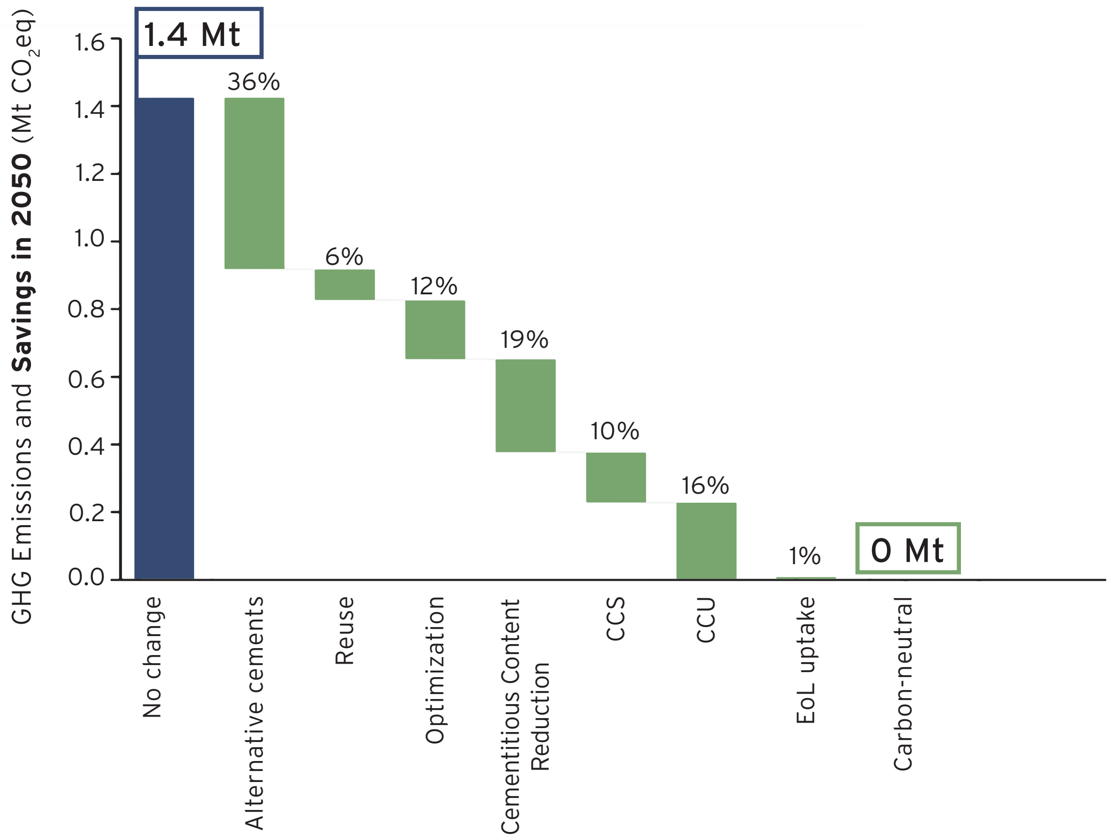


**Figure 1.** Effectiveness of the proposed ambitious solutions to attain carbon-neutral concrete for pavement application in 2050.

combination of solutions.

The second perspective (**Figure 2**) considers the cumulative emissions between 2017 and 2050 when three different scenarios (shown in **Table 1**) were implemented. These scenarios are a 'no change' scenario in which 2017 practices are maintained throughout the analysis period; a projected scenario in which solutions are implemented according to expected trends (see **Table 1**); and an ambitious scenario where more active measures are taken to reduce GHG emissions to net-zero by 2050.

In the proposed ambitious scenario, seven different GHG reduction solutions were considered. Those include: alternative cements, such as portland limestone cement (PLC), along with slag and fly ash; the optimization of concrete structure design; improving the particle packing or cementitious content in concrete; the reuse of concrete materials; carbon uptake by spreading demolished concrete at end-of-life (EoL); carbon capture and storage (CCS) at cement plants; and carbon capture and utilization (CCU), in which captured carbon is used for synthetic aggregate production. Since more than 80% of concrete's weight consists of aggregates, concrete has the potential to become a relatively large and permanent carbon sink.

## Reaching Net-zero

The results of this analysis show that carbon-neutral concrete mixtures are feasible and that ambitious actions can significantly reduce the GHG emissions from



77 Massachusetts Ave, 1-274, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu

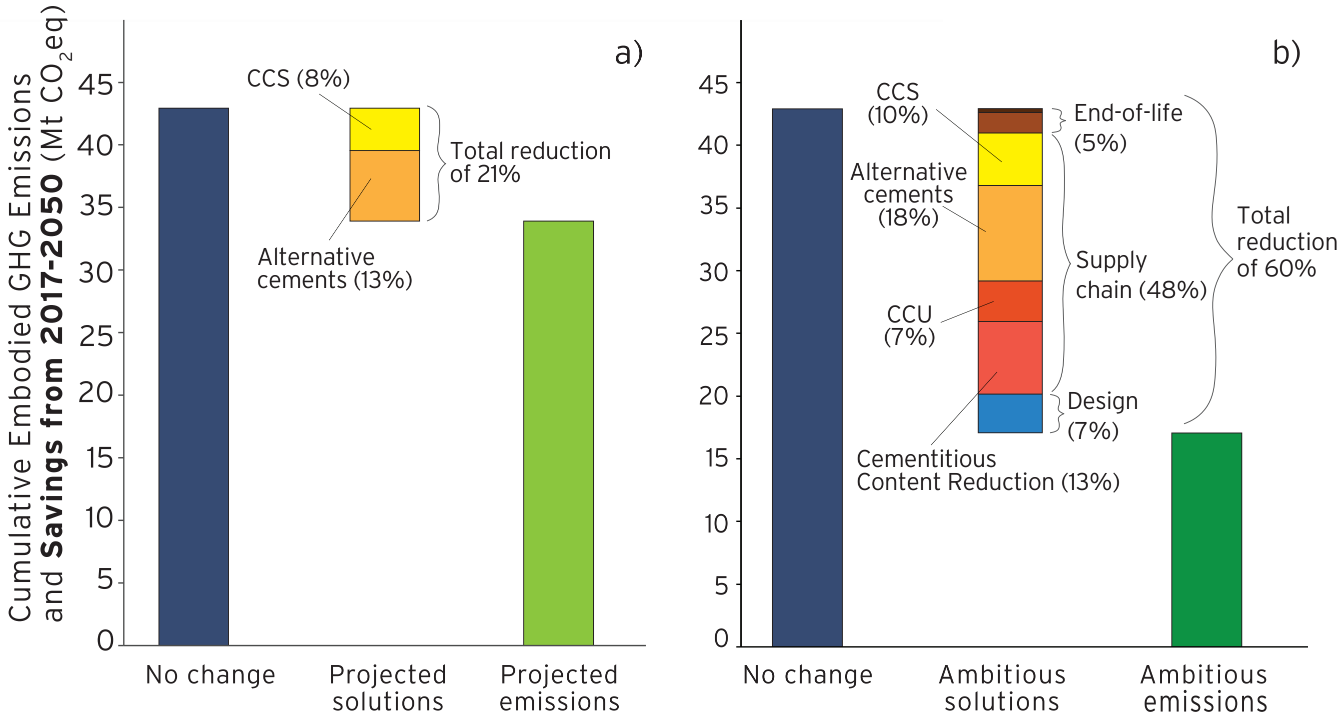


Figure 2. Cumulative embodied GHG emissions and savings of the U.S. concrete pavements under the **a)** projected and **b)** ambitious improvement scenarios during the 2017-2050 period. The solutions shown in 2b are from the same ambitious scenario shown in Figure 1 and Table 1 and would, therefore, also represent carbon neutrality in 2050.

the concrete used in the U.S. pavement sector over the next several decades.

These ambitious actions are shown in Figure 1, which includes the GHG reductions for each action in 2050 when the carbon-neutral concrete is achieved. Of these solutions, the most significant is cementitious content reduction, which would result in a 0.66 Mt $CO_2$eq saving. When alternative cements, like portland limestone cement with pozzolanic materials, replace 50% of portland cement, an additional 0.24 Mt $CO_2$eq can be saved. On top of this, reusing demolished concrete slabs and optimizing the structure design can add up to a reduction of 0.15 Mt $CO_2$eq. CCS and CCU (operated with renewable energy) make up the remainder of the GHG reductions.

Though the implementation of these solutions will likely vary by location, this level of adoption—if implemented across the U.S. as a whole—would achieve net-zero in 2050. It's important to note that while the scope of this analysis extends only to the pavements sector, attaining net-zero concrete by 2050 in the building sector is also possible. In fact, the pathways for net-zero concrete in buildings should strongly resemble those for pavements—but likely with some differences in the order of solutions. However, further research must be conducted to realize and solidify those pathways.

In addition to the emissions reductions possible in 2050, the cumulative emissions reductions (see **Figure 2**) attainable from the scenarios shown in Table 1 were also quantified. In the 2017-2050 analysis period, the embodied GHG emissions of concrete pavements can be reduced by 21% and 60% under the projected (**Figure 2a**) and ambitious scenarios (**Figure 2b**), respectively. Most of the savings in the projected and ambitious improvement scenarios come from the solutions in the cement and concrete supply chain (i.e., alternative cements and cementitious content reduction).

While these GHG savings are attainable, they will require regionally specific policies to identify barriers and solutions to meeting carbon neutrality goals. Moreover, to fulfill the carbon-neutral scenario, a comprehensive program of investments will be required. One challenge is the cost uncertainty associated with CCS/CCU pathways and the necessity of supplying the operational energy of these technologies with renewable electricity sources. This is particularly challenging since the CCS cost from a cement plant is among the highest of all industries.[1] In addition, the implication of CCU in synthetic aggregate requires a significant scale-up effort and the long-term performance of concrete pavements built with these aggregates should be tested. Hence, these embodied impact reduction strategies must receive support in much the same way that renewable energy technologies have been supported.

**Table 1.** Pavement system GHG reduction strategies for system solutions under projected and ambitious improvement scenarios.

| Solution | No Change | Projected | Ambitious |
|---|---|---|---|
| Alternative Cements [2], [3] | Different states (15-25 %wt. of portland cement) | 40% portland cement replacement by 2050 | 50% portland cement replacement by 2050 |
| Particle Packing (Cementitious Content) [4], [5] | 345-470 kg binder/$m^3$ | No implementation | Improve the particle packing to 195 kg binder/$m^3$ |
| Design Optimization [6], [7] | No implementation | No implementation | 19% reduction in the concrete consumption per unit of area |
| Reuse of Concrete Elements [6] | No implementation | No implementation | 0.1 $m^3$ reuse per cubic meter concrete |
| End-of-life Carbon Uptake [8] | No implementation | No implementation | Extending the spreading period to three years |
| CCS [3] | Near to 0% in the US | 100% of the average tech by 2050 | 100% of the best performing tech (full oxy-fuel) by 2050 |
| CCU [9] | Near to 0% in the US | No Implementation | 14% of the total supplied aggregates for pavements by 2050 |
| Operational Energy [10] | 0.1-0.72 kg $CO_2$/kWh | EIA Projection (2-38% reduction by 2050) | Operation with full Renewable energy (0.02 kg $CO_2$/kWh) |

## Related Links:

- CSHub Embodied Carbon Research
- CSHub Pavements Research

## Citation:

AzariJafari, Hessam. (2021). "Solutions for Net-zero Carbon Concrete in U.S. Pavements," CSHub Research Brief. Volume 2021, Issue 5.



77 Massachusetts Ave, 1-274, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu

# References

**[1]** N. Thonemann and M. Pizzol, "Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry," Energy Environ. Sci., vol. 12, no. 7, pp. 2253–2263, 2019, doi: 10.1039/c9ee00914k.

**[2]** NRMCA, "Environmental Product Declaration INDUSTRY-WIDE EPD FOR READY MIXED CONCRETE Environmental Product Declaration," Silver Spring, MD, 2020. [Online]. Available: https://www.nrmca.org/wp-content/uploads/2020/02/EPD10080.pdf.

**[3]** IEA, "Technology Roadmap - Low-Carbon Transition in the Cement Industry," 2018. [Online]. Available: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

**[4]** B. L. Damineli, F. M. Kemeid, P. S. Aguiar, and V. M. John, "Measuring the eco-efficiency of cement use," Cem. Concr. Compos., vol. 32, no. 8, pp. 555–562, 2010, doi: 10.1016/j.cemconcomp.2010.07.009.

**[5]** K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-$CO_2$ cement-based materials industry," Cem. Concr. Res., vol. 114, no. February, pp. 2–26, 2018, doi: 10.1016/j.cemconres.2018.03.015.

**[6]** G. Habert et al., "Environmental impacts and decarbonization strategies in the cement and concrete industries," Nat. Rev. Earth Environ., vol. 1, no. 11, pp. 559–573, 2020, doi: 10.1038/s43017-020-0093-3.

**[7]** MIT Concrete Sustainability Hub, "Supplementary Information for Comparative Pavement Life Cycle Assessment and Life Cycle Cost Analysis", 2014. Available: http://cshub.mit.edu/sites/default/files/documents/Supplementary%20Information%20V2.pdf.

**[8]** H. AzariJafari, F. Guo, J. Gregory, and R. Kirchain, "Carbon uptake of concrete in the US pavement network," Resour. Conserv. Recycl., vol. 167, no. October 2020, p. 105397, 2021, doi: 10.1016/j.resconrec.2021.105397.

**[9]** National Academies of Sciences Engineering and Medicine, Gaseous carbon waste streams utilization: Status and research needs. United States of America: National Academies Press, 2019.

**[10]** U.S. EIA, "Annual Energy Outlook 2019," Washington DC, 2019.

---

**This research was carried out by CSHub with sponsorship provided by the Portland Cement Association and the Ready Mixed Concrete Research & Education Foundation. CSHub is solely responsible for content.**



77 Massachusetts Ave, 1-274, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu