PERSPECTIVE

Road Map to Carbon Neutrality for Concrete Materials

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Greenhouse gases and climate change affect all aspects of society. The construction materials industry is no exception, with a persistent focus on concrete and cement in particular. Design professionals often conflate the embodied carbon of materials with the environmental performance of building systems. This mistakenly neglects the role of life-cycle analysis (LCA) and fails to integrate the overall impact of selecting building materials to best address climate change. The Portland Cement Association's recently released *Road Map to Carbon Neutrality*[1] addresses this confusion by adopting a value-chain approach.

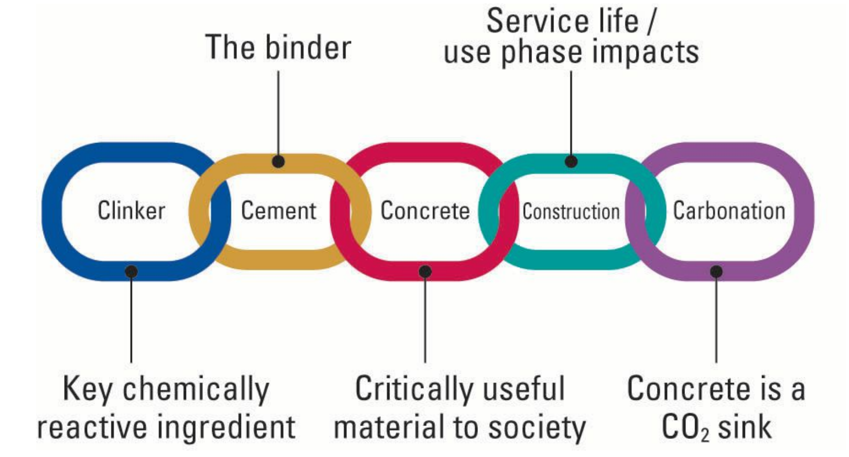
This road map to carbon neutrality encompasses the entire value chain of cement and concrete: clinker, cement, concrete, construction, and the use of concrete as a carbon sink. This approach recognizes that each link in the chain has a specific role to play in addressing the reduction or avoidance of greenhouse gases and that no individual link should be considered in isolation.

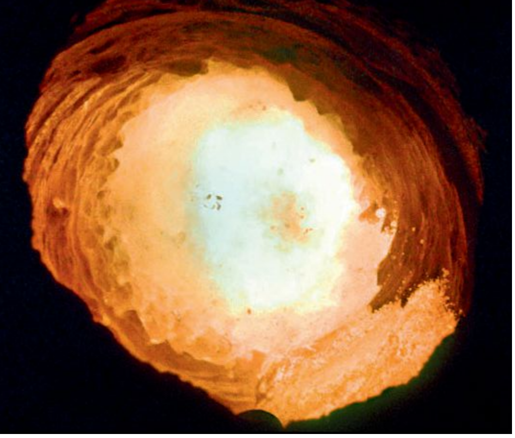
Clinker is the first step in the value chain. Clinker is an intermediate product within the cement manufacturing process and represents the initial contribution to the carbon dioxide (CO_2) footprint of concrete structures. The production of clinker requires the decarbonation of limestone as a precursor to the formation of calcium silicates and other phases. Decarbonation requires material temperatures approaching 2800°F (1500°C), which are achieved through fuel combustion. Slightly less than 40% of the CO_2 released in the production of clinker is generated through fuel combustion, while slightly more than 60% of the CO_2 released is the result of the decarbonation of calcium carbonate ($CaCO_3$). These two sources of CO_2 can be reduced by increasing the proportion of decarbonated raw materials and transitioning from traditional fossil fuels to lower-carbon fuels, alternative fuels, and transformative fuels such as hydrogen. Longer-term solutions will require carbon-capture technologies such as solvents, sorbents, and membranes, along with less-traditional capture technologies such as oxy-calcination, direct separation calcination, calcium or carbonate looping, and algae capture.

The reduction of CO_2 in the clinker production process can be further leveraged within the cement portion of the value chain, primarily through the use of nonclinker ingredients such as limestone and supplementary cementitious materials (SCMs). Portland-limestone cements Type IL, as specified by ASTM C595, *Standard Specification for Blended Hydraulic Cements,*[2] or AASHTO M 240, *Standard Specification for Blended Hydraulic Cement*,[3] provide a great example of using technology to reduce CO_2 emissions. In these cements, the amount of clinker is reduced, and within proper limits, they provide concrete strength and durability that is comparable to unblended cements. Transitioning from prescriptive-based cement specifications to performance-based cement specifications provides further opportunities to either reduce or avoid CO_2 emissions.

Focusing solely on clinker or cement overlooks the influence that concrete mixing, manufacturing, and construction practices have on the reduction and avoidance of greenhouse gas emissions. For example, concrete manufacturing can be transitioned to renewable electricity, and the transportation of concrete and concrete products can be transitioned to zero-emission vehicles.

The value chain of cement and concrete. All Photos and Figures: Reprinted from Wilson, M. L., and P. D. Tennis. 2021. *Design and Control of Concrete Mixtures*, 17th ed. Skokie, IL: Portland Cement Association.



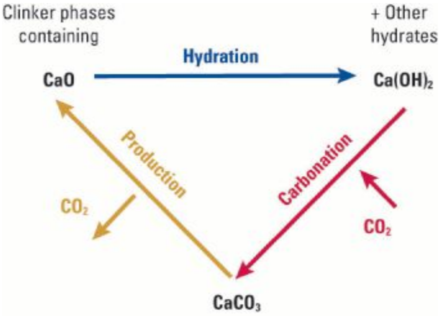


The interior of a rotary cement kiln. More than 60% of the CO_2 produced during cement manufacturing results from the calcination process whereas just under 40% results from the combustion required to reach material temperatures of approximately 2800°F (1500°C).

However, the single greatest opportunity for CO_2 reductions in concrete as a material remains with mixture optimization. Concrete mixtures can be optimized by increasing the use of SCMs and using machine-learning algorithms and other methods of artificial intelligence to discover the optimal mixture proportions for specific applications and to identify the optimal sequencing, scheduling, and delivery of concrete and concrete products. Optimized concrete mixtures can provide the best strength and durability performance and the most sustainable performance for specific applications. Quality assurance and acceptance testing of fresh concrete can also be optimized to provide better performance with less variability.

The use phase of a building accounts for 88% to 98% of the life-cycle environmental impact. Research by the Massachusetts Institute of Technology indicates that using concrete lowers the use-phase global-warming potential of a structure by up to 10% and lowers the life-cycle global-warming potential impacts by up to 8% compared with buildings that are not concrete.[4] By using LCA, integrated design principles, and performance-based specifications for construction materials, design professionals can optimize performance and reduce the embodied carbon, not just through lower-carbon cement and concrete mixtures but also through increased energy and operational efficiency, reduced maintenance and replacement, and an extended service life. The CO_2 associated with construction can be further reduced or avoided through innovative construction techniques such as additive manufacturing, a zero-waste construction site, advanced sequencing and scheduling, zero-emission deliveries, and zero-emission material-handling equipment. It should be noted that a cradle-to-gate LCA, which considers the life cycle of a product until it is ready to leave the production facility and be delivered to the construction site, does not encompass the complete impacts of a cradle-to-grave LCA or functional unit perspective. A cradle-to-gate LCA looks at an individual product such as a cubic yard of concrete, whereas a cradle-to-grave LCA looks at how the concrete is ultimately used and how the structure performs over its service life and decommissioning.

The final step in the value chain is the use of concrete as a carbon sink. Concrete absorbs CO_2 throughout its entire life through a process called carbonation. Air contains about 0.04% or 400 ppm of CO_2. That CO_2 naturally diffuses into concrete and reacts with the calcium hydroxide ($Ca[OH]_2$, a product of the cement hydration reaction) to form calcium carbonate ($CaCO_3$). The amount of CO_2 absorbed by concrete is limited to the amount released by calcination during clinker manufacture and the use of SCMs in concrete. The rate at which it is absorbed depends primarily on the concrete surface area exposed to the atmosphere, the amounts of water and moisture available, and the length of exposure. Various models using the compressive strength of the concrete, the type of structure, the type of exposure (exposed to rain or sheltered, indoor or outdoor, with or without cover, below or above ground) have been developed to calculate the degree of carbonation. Current estimates indicate that approximately 10% of the CO_2 generated during the manufacture of cement and concrete can ultimately be absorbed over the life of a concrete structure. Carbonation of good-quality concrete is acceptable, provided it does not reach the reinforcing steel. Ideally, the service life of the structure will be reached long before the carbonation reaches reinforcing steel. Carbonation of poor-quality concrete is not advocated because an increased level of permeability will allow the carbonation to reach the reinforcing steel while the structure is still in use. After the concrete structure has been demolished, the exponential increase in the surface area of the concrete allows a corresponding increase in the rate of carbonation.



The calcination–hydration–carbonation relationship. The carbonation reaction, concrete absorbing carbon dioxide to form calcium carbonate ($CaCO_3$), is the opposite of the calcination reaction, where $CaCO_3$ is transformed into calcium oxide (CaO) prior to the complex chemical reactions that form clinker and that are ultimately used to produce portland cement.

The value-chain and LCA approaches both recognize that concrete provides a valuable solution that balances society's need for a sustainable and resilient built environment while simultaneously addressing the urgent need to reduce greenhouse gases. Thus, these approaches validate the adage, "The whole is better than the sum of its parts."

References

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