COMMENTARY

Decarbonizing construction through carbonation

Jacob Schneider[a,1]

It is probably safe to assume that most of us are aware of the magnitude of carbon dioxide (CO_2) emissions on an annual basis, on the order of billions of metric tons (gigatons), and that an appreciable percentage of that CO_2 can be attributed to industrial emitters (1) such as cement plants, steel plants, and the aluminum industry, to name the most prominent ones. Cement plants alone contribute to over 5% of global CO_2 emissions annually (2), which is reason enough to focus basic research efforts on reducing the carbon intensity of that industry, as for example, Ellis et al. (3) have done in PNAS, where they report findings on the production of cement using electrochemical synthetic methods driven by renewable energy and coproducing hydrogen gas—a valuable industrial raw material in its own right—via a proposed process that would epitomize the circular economy. The work is on-topic to a movement of local, state, federal, and even international legislation that seeks to do something proactively about the increasing CO_2 concentration in Earth's atmosphere. The authors present an alternative, low-carbon approach to the preparation of alite (Ca_3SiO_5 or $3CaO{\cdot}SiO_2$ or, in cement chemist notation, C_3S), which is the major mineral phase of Portland cement. The conventional manufacture of Portland cement, on the other hand, uses fossil fuels as an energy source to calcine limestone ($CaCO_3$) and other raw materials in a cement kiln; the process yields CO_2 emissions from both fossil fuel combustion and from decomposition of $CaCO_3$ in the kiln. The industry is certainly aware of this and, it seems, is taking action on a global scale (Cement Association of Canada, https://www.cement.ca; The European Cement Association, https://cembureau.eu/home; Portland Cement Association, https://www.cement.org; World Cement Association, https://www.worldcementassociation.org). The typical range of CO_2 produced during the manufacture of Portland cement, which is quite extensive, is roughly 0.5 mass units to 1.1 mass units of CO_2 per equivalent mass unit of Portland cement produced; that is, a ratio of 1.0 indicates 1 ton of CO_2 for every

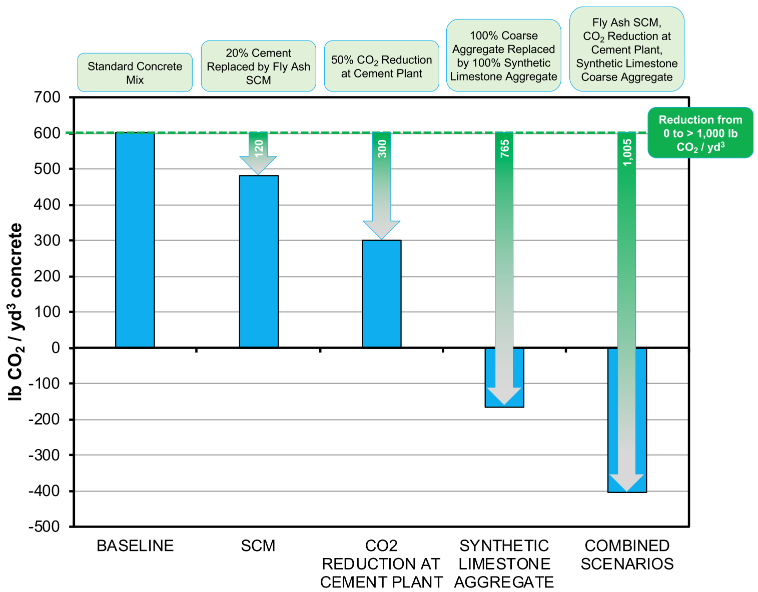

Fig. 1. A comparison of 5 concrete mixes illustrates the effect, in pounds of CO_2 per cubic yard of concrete (lb CO_2/yd^3), of using different formulations to reduce the carbon impact in the concrete product by offsetting and/or sequestering CO_2. The arrows indicate the lb CO_2/yd^3 reduction compared to the Baseline scenario, while the blue bars indicate a quantitative carbon rating for the concrete mix in each scenario. Details of the concrete mixes are discussed in text.

metric ton of Portland cement produced. Across the industry, improving or lowering this ratio is an active area of research and development, but this obective is easier said than done, lending an urgency to basic research in this direction.

A commercial cement plant will produce roughly 1,000,000 tons of cement annually, and, as with any large industry using decades-old commercial processes, implementing new technologies that do not fit seamlessly in with the old can be very disruptive to plant operations and, importantly to those owning the assets, can also be uneconomical. This is especially true for cement. The material has to be kept dry to

[a]Research and Development, Blue Planet, Ltd., Los Gatos, CA 95032

Author contributions: J.S. wrote the paper.

Competing interest statement: J.S. is an employee of Blue Planet, Ltd., a for-profit company that has its own carbon capture and mineralization technology that produces $CaCO_3$ products for use in construction.

See companion article on page 12584.

[1]Email: jake@blueplanet-ltd.com.

First published September 18, 2019.

avoid hydration. It does not travel far, due, in part, to its high surface area and density, roughly 300 m^2/kg to 400 m^2/kg and 3.15 g/cm^3, respectively. The end use for cement is concrete, a market that places tens of gigatons of concrete annually, but has slim profit margins in most applications. In addition to all of the above, the performance characteristics of the cement are most critical. While concrete is composed of coarse aggregate, fine aggregate (sand), water and cement (yes, they are concrete trucks and not cement trucks), it is the cement that holds all of the components together to maintain the structural integrity for a given construction application. For those and other reasons, changing the upstream manufacture of cement in an already conservative industry can be a major challenge, with significant risks to specifiers and end users. There are, however, other ways to decarbonize the industry, and they involve carbonating or, more specifically, storing CO_2 in the concrete.

What this commentary highlights is the potential for concrete to offset and/or sequester CO_2, the irony being that concrete, at least in its conventional form, isn't necessarily an environmentally friendly material. The aggregate rocks are typically mined from quarries and transported to local markets via truck, rail, or ship (preferably one of the latter 2 modes). The cement is transported similarly and, as discussed, is the real CO_2 factor in the concrete mix, so much so that the CO_2 impact from the other constituents in concrete is essentially in the noise compared to the cement. That said, there are already a number of developing technologies that are aware of the opportunity to store CO_2 in concrete (Blue Planet, Ltd., http://www.blueplanet-ltd.com; Carbicrete, http://carbicrete.com; O.C.O Technology Ltd., https://oco.co.uk; CarbonCure Technologies, https://www.carboncure.com; CO2Concrete, https://www.co2concrete.com; Solidia Technologies, https://solidiatech.com). Fig. 1 illustrates how this can happen; it includes scenarios that compare the carbon impact of 5 concrete mixes relative to a baseline mix, each scenario using a different formulation to offset, sequester, or both offset and sequester CO_2 in the concrete itself.

The Baseline scenario represents a rudimentary medium-strength concrete formulation, a mix that has 600 lb of Portland cement, 1,739 lb of coarse aggregate, 1,429 lb of fine aggregate, and 300 lb of water per cubic yard of concrete, for a total mass of 4,069 lb/yd^3 (4). In this Baseline scenario, there is no carbon offset or sequestration, and the quantitative carbon rating of this mix is 600 lb of CO_2 per cubic yard of concrete; all other scenarios will be in reference to this mix design.*

The second, supplementary cementitious material (SCM) scenario is one that is most commonly used in industry to offset carbon, and that is by replacement of Portland cement with, for example, 20% SCM such as fly ash from coal combustion or slag cement, a downstream byproduct of the steel industry. This, however, can be tricky in some markets, as there is not enough supply of SCM, or it is simply too costly to transport. Using the same formulation as the Baseline scenario, but replacing 20% of the Portland cement with fly ash, SCM results in a carbon offset of 120 lb of CO_2/yd^3. Likewise, the quantitative carbon rating of the concrete has been reduced from 600 lb down to 480 lb of CO_2/yd^3 in the SCM scenario. Note that this reduction by 120 lb of CO_2/yd^3 is not CO_2 that is sequestered but is CO_2 that has been offset by using the SCM in place of the cement, that is, the 120 lb of cement that was replaced in the mix may have still been manufactured, but it was used in a different project. It is also important to note that, although SCMs have their own carbon intensity from processing and from transportation, as byproducts from heavy industry, they are often given a free pass when it comes to carbon counting; the alternative to using SCMs in concrete is to landfill the materials, which is quite costly from both an environmental and a liability perspective.

Cement plants alone contribute to over 5% of global CO_2 emissions annually, which is reason enough to focus basic research efforts on reducing the carbon intensity of that industry, as for example, Ellis et al. have done in PNAS.

A third scenario, CO_2 Reduction at Cement Plant, represents a mix that uses cement manufactured at a plant that has 50% of its carbon footprint reduced at the plant. It could be reduced by, for example, using conventional carbon capture to capture the CO_2 emissions from the normal cement manufacture process at the flue gas stack, or the carbon could be reduced, for example, by a technology that more efficiently produces Portland cement, such as an electrochemical process as is described by Ellis et al. (3). This scenario offers up a 2-for-1 advantage to the cement manufacturer. Not only is there a reduction in the ratio of Portland cement to CO_2 emissions, from 1:1 to 1:0.5, but this also presents a potential market advantage to competing manufacturers. This scenario uses the same mix formulation as the Baseline scenario, using 600 lb of Portland cement; however, since the carbon intensity of the cement is reduced by 50%, the overall carbon reduction is 300 lb of CO_2/yd^3, a 30% greater impact compared to the SCM scenario. The CO_2 Reduction at Cement Plant scenario can get rather confusing when accounting for carbon as offset or as sequestered. If 50% of the CO_2 were captured at the cement plant, its downstream destination could vary greatly, and the accountability of that captured carbon becomes a shell game, one that is better left for debate elsewhere.

A fourth scenario, called Synthetic Limestone Aggregate, considers replacement of all of the coarse aggregate in the Baseline mix with synthetic $CaCO_3$ aggregate, for example, synthetic $CaCO_3$ that has been produced from a carbon capture and mineralization/utilization technology that converts gaseous CO_2 into solid carbonate (CO_3^{2-}) when it is combined with a source of calcium (Ca^{2+}). In this scenario, the carbon reduction potential is remarkable. Not only is the carbon sequestered—as opposed to merely offset—but the overall mass of aggregate in the concrete formulation is substantial such that the mix formulation has a reduction in carbon by greater than 765 lb of CO_2/yd^3 from the Baseline and now has a quantitative carbon rating that is negative by 165 lb of CO_2/yd^3. (It is assumed, in this scenario, that a synthetic $CaCO_3$ aggregate is 44 wt% CO_2. Although there is likely to be some energy load associated with the upstream manufacturing of the synthetic $CaCO_3$ aggregate, the author has chosen not to assume any such load for this case study.)

*With the support of the Standards Council of Canada (SCC), the Canadian Standards Association (CSA) is working to develop a technical specification of a quantitative carbon rating system known as the CARBONSTAR rating, a rating system that was originally conceptualized by Blue Planet, Ltd. For the concrete formulations in each scenario, it is assumed that 1.0 lb of CO_2 is emitted for every 1.0 lb of Portland cement produced and that the CO_2 emissions from the other constituents in the concrete are 0.0 lb of CO_2; that is, the CO_2 footprint for the concrete is solely accounted for by the quantity of cement in each formulation.

A Combined Scenario, one that is inclusive of all of the components from the SCM, CO_2 Reduction at Cement Plant, and Synthetic Limestone Aggregate scenarios, demonstrates a carbon reduction potential that really gets to the point, reducing CO_2 by more than 1,000 lb of CO_2/yd^3 compared to the Baseline and resulting in a concrete mix that is negative in CO_2 by more than 400 lb/yd^3. What's more, the impact really hits home when you consider the size of building projects that could use this type of concrete formulation. For example, the construction of the recently completed Salesforce Tower located in San Francisco, CA, which now dominates the city's skyline, placed nearly 100,000 yd^3 of concrete. Imagine if the Combined Scenarios mix design were used for all of this concrete: Then the structure itself would have reduced carbon by more than 100,500,000 lb of CO_2 in a combination of offset and sequestration, an amazing thought to consider. Not only that, oftentimes, "green" or recycled materials carry the connotation that they are lesser when it comes to performance; however, the Combined Scenarios doesn't jeopardize concrete performance, because it still has 80% of the cement from the Baseline scenario, and, although it always comes down to testing, keeping cement in the formulation grants architects and engineers the reliability they need during specification of concrete.

The above examples illustrate the potential for CO_2 reduction that the cement and concrete industries have at their fingertips. No other human-made material in the world is used more than concrete, and, interestingly enough, it is used at the same gigaton scale as there are annual CO_2 emissions. US policy makers are taking notice, as is evidenced by Section 45Q in the Bipartisan Budget Act of 2018, which includes legislation on tax credits for CO_2 capture and beneficial reuse. Standardized product category rules are being written by industry leaders as a means to develop environmental product declarations (EPDs) for products such as those described above, for example, synthetic $CaCO_3$ aggregates made from captured CO_2. EPDs then serve as certified classifications for building products, and are fed into product life cycle analyses. These analyses are used by the design firms and general contractors to help guide the specifications on a construction project. And, while project cost will always remain a key factor in construction, the building landscape is looking more and more like one that has a lot of carbon in it. As such, there is no better time than the present to rethink established processes in the industry. Though a single solution is not likely, reexamining old chemistry, as Ellis et al. (3) have exemplified in their approach to making a low carbon cement, is paramount to innovation and change going forward.

1 Intergovernmental Panel on Climate Change, *Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* O. Edendhofer, Ed. (Cambridge University Press, New York, NY, 2014).

2 R. M. Andrew, Global CO_2 emissions from cement production. *Earth Syst. Sci. Data* **10**, 195–217 (2018).

3 L. D. Ellis, A. F. Badel, M. L. Chiang, R. J.-Y. Park, Y.-M. Chiang, Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating $CaCO_3$ while producing useful gas streams. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 12584–12591 (2019).

4 P. K. Mehta, P. J. M. Monteiro, *Concrete: Microstructure, Properties and Materials* (McGraw-Hill, New York, NY, ed. 3, 2006).