Concrete Solutions to Climate Change

How Local Policy Can Promote Sustainable Construction Activities

Matthew P. Adams

June 2021

Rockefeller Institute of Government

ABOUT THE AUTHOR

Matthew P. Adams is a Richard P. Nathan public policy fellow at the Rockefeller Institute of Government and an assistant professor in the John A. Reif, Jr. Department of Civil and Environmental Engineering at the New Jersey Institute of Technology.

Concrete Solutions to Climate Change

How Local Policy Can Promote Sustainable Construction Activities

The American Jobs Plan proposed by President Biden is, at its core, an infrastructure improvement bill.[1] If passed, it aims to repair 20,000 miles of highway and 10,000 bridges, and repair, replace, or expand water infrastructure, schools, hospitals, and government buildings. All of this work would require a massive investment in construction materials, such as concrete, wood, asphalt, and steel. The proposed bill also seeks to prioritize sustainability in the choice of construction materials and practices.[2] Concrete, which is the second most used material in the world, would play a central role in the construction and rehabilitation that comes with this proposed infrastructure investment, however it also has a significant carbon footprint.[3] While methods of decreasing the environmental impact of concrete have been developed, they have not been broadly adopted by producers. As discussed in this brief, flexible municipal policies that can adjust for local availability of materials, project specific needs, and funding, can offer a model for encouraging adoption of low-embodied carbon concrete. Further, existing municipal-level policies may scale to the state and federal level.

One of the key goals when considering sustainability is the reduction of embodied carbon. Embodied carbon is a measure of the total amount of carbon dioxide (CO_2) released during the production, transportation, and use of a product. CO_2 is one of the most significant greenhouse gases and release of CO_2 into the atmosphere is a major cause of global climate change. Worldwide, the production of concrete accounts for about 8 percent of the total CO_2 released each year.[4]

While concrete actually has relatively low-embodied carbon per unit volume compared to other building materials, the massive scale at which it is employed results in the significant release of carbon into our atmosphere. Despite this, many concrete mixtures are designed with a focus solely on concrete strength, ignoring the need for more nuanced approaches that optimize strength, durability, and lower carbon emissions.

With the recent demand for more sustainable construction, owners and contractors have started using "low-carbon concrete" in construction; however, this term is a widely used catchall for many different types of concrete mixtures. In practice, "low-carbon concrete" refers to any concrete mixture that has lower embodied carbon than a mixture containing only portland cement and natural aggregates, that utilizes design techniques that reduce overall cement content, or that utilizes any advanced carbon capture or storage technologies.

Many years of ongoing research and application have shown that low-carbon concrete options can achieve a range of strengths adequate for many different applications and even improve long-term durability compared to more conventional mixtures.[5] Research has also shown that reconsidering our basic approach to concrete mixture design may result in significant greenhouse gas emissions reductions.[6] A 2018 report from the International Energy Agency and industry-supported Cement Sustainability Initiative, for example, outlined a roadmap to achieve a 24 percent reduction in industry emissions by 2050.[7] But even though low-carbon concrete technologies have a long history of excellent performance and potential to reduce emissions, some engineers and concrete producers are hesitant to specify them for new concrete construction.

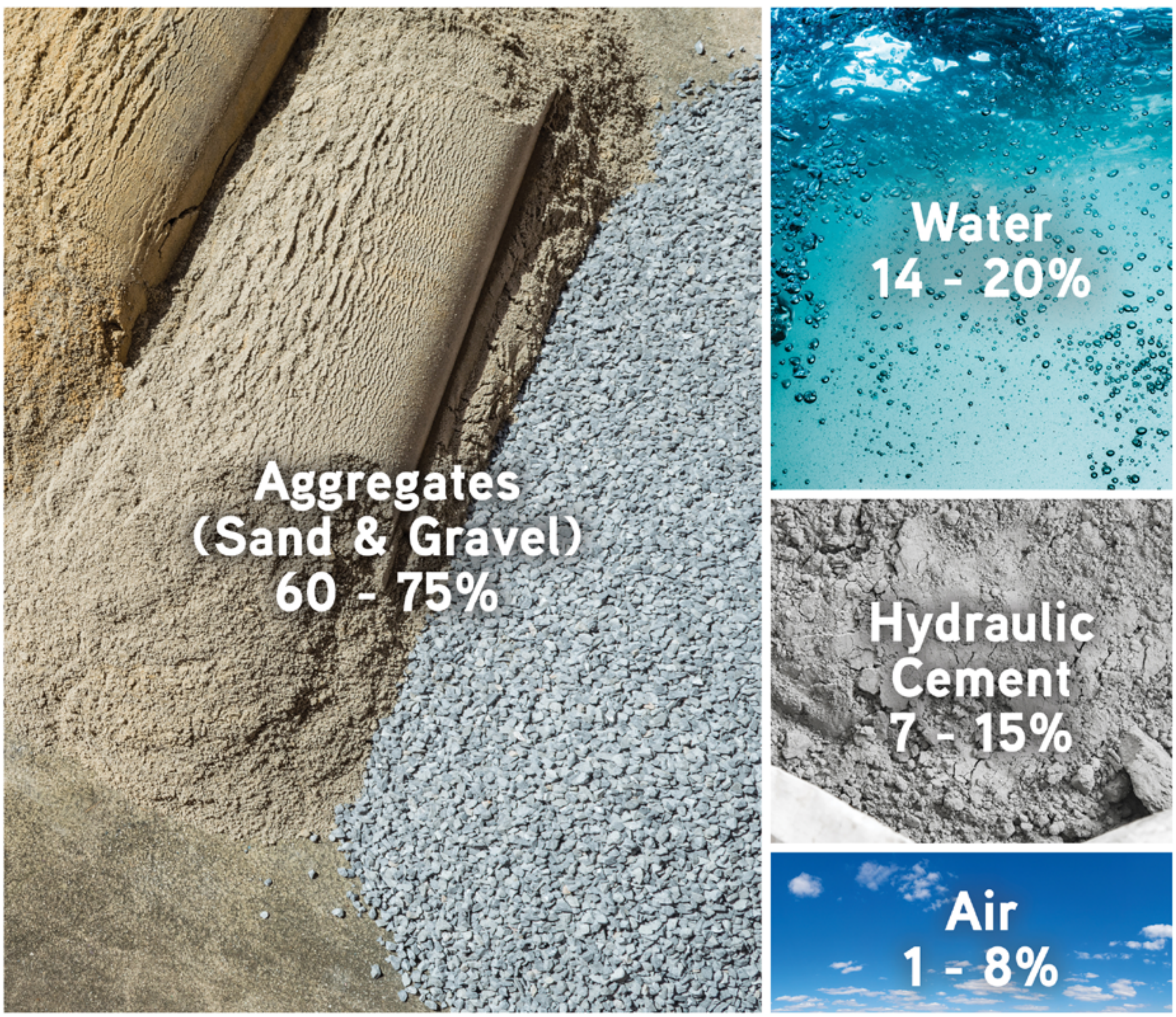
Local, state, and federal government agencies are the largest procurers of concrete.[8] Thus, it is common for even private construction firms to base their concrete mixture specifications on ones designed for state applications. Relying primarily on private industry to independently drive changes in concrete mixture designs, however, may not necessarily result in a significant impact on the overall carbon footprint of concrete. It is therefore important to understand how local, state, and federal procurement and infrastructure policies might be crafted to increase the use of low-carbon concrete. In this piece, I will outline the climate impacts of concrete and the development and use of low-carbon concrete, and discuss local policies related to its use. In particular, I consider a case study of the Village of Hastings-on-Hudson in Westchester County, New York, which passed a resolution in 2020 to promote the use of low-carbon concrete in its procurement operations.

Carbon in Concrete

A typical concrete mixture contains Portland cement (often just referred to as "cement"), water, sand, and gravel. Understanding how cement relates to concrete is as simple as thinking of a chocolate chip cookie. Cement is like the flour that when mixed with water and egg will bind the chocolate chips, which are like the sand and gravel, together into a cookie. Cement is produced at cement plants where ground up limestone and clay are combined in a large rotating kiln and heated to temperatures in excess of 2550°F. During this heating process, the limestone (calcium carbonate) breaks down to calcium oxide, releasing carbon dioxide. This process results in a chemical transformation of the limestone and clay and produces clinker, which resembles chunks of porous rock about one inch or less in diameter. The clinker is then mixed with gypsum, a sulfate bearing mineral necessary for controlling the rate at which concrete hardens, and ground down into a very fine powder. That powder is Portland cement.

After grinding, the cement is then transported to concrete plants where it is mixed with sand and gravel, also referred to as aggregates, which are generally quarried nearby the plant and transported over roadways, as well as water. The combination of the sand, gravel, water, and cement is what is known as concrete. The concrete is then transported over roadways to the construction site (cast-in-place) or cast at the plant with the finished element and then transported to the final construction site (precast). Cast-in-place concrete is concrete that arrives at the construction site in a fresh or flowable state. It is poured into forms and allowed to harden and gain strength in place. Precast concrete is poured and allowed to harden at the concrete plant. The concrete components of a building (e.g., beams, wall panels, etc.) are then shipped to the construction site and assembled, similar to toy blocks (but much better connected).

FIGURE 1. **Typical Concrete Material Components**



As noted above, concrete is responsible for about 8 percent of the total CO_2 released into the atmosphere from anthropogenic (human-related activity) sources each year.[9] Despite the large amount of CO_2 produced overall, concrete has a relatively low carbon footprint per unit volume when compared with other common building materials. Concrete production releases 0.29 pounds of CO_2 per pound of concrete that is produced, compared to 0.81 pounds of CO_2 per pound of plywood or 2.8 pounds of CO_2 per pound of steel produced.[10]

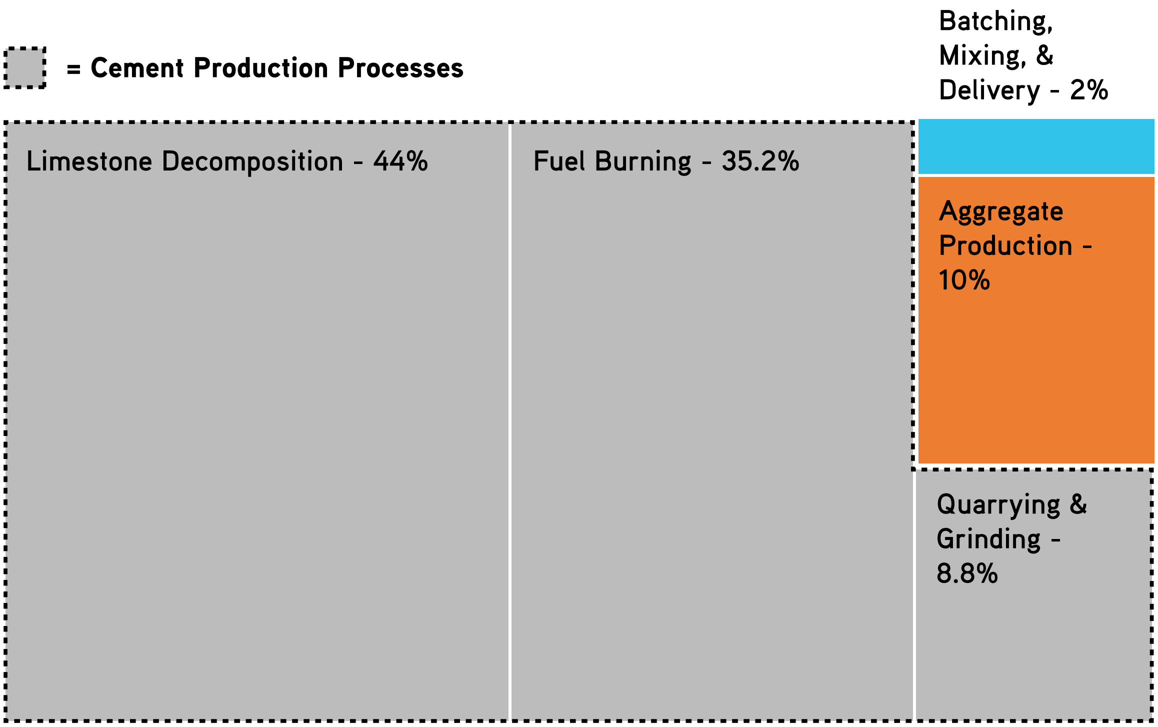
The scale at which we use concrete is what results in the large amount of CO_2 produced. Over 5 billion tons of concrete are cast each year worldwide, making it the world's most used building material—more than three times the combined annual use of wood, steel, and asphalt.[11] The rate at which we consume concrete is, however, expected to continue to increase for the foreseeable future, so understanding how we can reduce its carbon footprint is important for mitigating its climate-related impacts.[12]

The scale at which we use concrete is what results in the large amount of CO_2 produced. Over 5 billion tons of concrete are cast each year worldwide, making it the world's most used building material—more than three times the combined annual use of wood, steel, and asphalt.

In the United States, the average CO_2 emissions associated with concrete is around 500 pounds per cubic yard of concrete material produced.[13] The release of carbon in concrete is associated with multiple processes: the production of cement, the production of aggregates, and the mixing and transportation of the final concrete material. Despite only making up around 10 to 15 percent of the weight of concrete, cement production processes are responsible for roughly 88 percent of the total CO_2 emissions from concrete production. Ten percent of cement production comes from the quarrying and grinding of raw materials, 40 percent comes from burning fuel to heat up the kiln, and 50 percent comes from the release of CO_2 during the decomposition of the limestone. The release of CO_2 from the decomposition of limestone is an unavoidable consequence of making cement and the only way to mitigate it is to use less cement.

The remaining 12 percent of CO_2 emissions associated with concrete production results from the production and transportation of aggregates (10 percent) and the batching, mixing, and delivery of the final concrete product (2 percent).

FIGURE 2. **Carbon Emissions from Concrete and Cement Production**



Over the past few decades, cement production has become a more efficient process. This has been achieved through two main improvements: 1) the capture and reuse of heat from the kiln to preheat the ground up limestone and clay; and 2) switching from wet slurries of ground limestone and clay to dry powders, reducing the energy needed to dry the material before it can be heated to 2550˚F.[15] However, the increase in cement demand and production has eclipsed these efforts to reduce the total carbon footprint of the cement industry. Concrete, and therein cement, is so widely used because it is made from abundant raw materials that are available around the world, relatively easy for untrained laborers to work with, and relatively durable and strong in many applications. With respect to more immediate infrastructure and construction projects on the horizon, at present, no other construction material would be able to take the place of concrete and cement at the scale on which it is used worldwide.

Limitations on the abundance of raw material narrows the types of cement we can produce at the same scale as Portland cement, which uses limestone and clay—relatively abundant materials available worldwide. Some alternative cements have reduced carbon footprints because they do not require as much limestone, the decomposition of which releases CO_2, and instead use materials such as calcium sulfoaluminate cements, geopolymer systems, and phosphorous-based cements. However, in general these materials and systems either do not provide the same performance as Portland cement and can be more difficult to work with (e.g., setting quickly or requiring caustic chemicals for the reaction) or, in the case of phosphorous cements, require the use of minerals that are not as abundant and are also used for other products, such as fertilizers. Therefore, significant replacement of Portland cement with alternative materials and systems is unlikely in the near-term future.

In response to the growing demand for cement and the need to balance that with carbon reduction, the concrete industry and researchers have developed some ways to reduce the amount of Portland cement used. These include:

- **Technological Improvements in Proportioning:** New understanding and computer modeling have improved how concrete materials are proportioned such that less cement can be used without impacting strength.
- **Increased Durability:** A focus on long-term performance has resulted in concrete structures that last for much longer, reducing the cement required to repair or replace them. Historically, the long-term durability and performance of concrete systems were not significant parts of the design process. In the last few decades, life expectancy requirements for infrastructure have increased, necessitating changes in design philosophy. This has led to significantly longer service lives for infrastructure, reducing the frequency with which infrastructure needs to be replaced or repaired. Deferring replacement of infrastructure means that no additional embodied carbon from the materials used to build the infrastructure is required.
- **Carbon Capture and Storage:** Developments in methods to capture carbon released during the cement production process are gaining traction. As carbon capture is combined with technology that can sequester carbon in new concrete, even more CO_2 reduction is being achieved.
- **Supplementary Cementitious Material (SCM):** SCMs are materials that can be used to replace a portion of the Portland cement in a concrete mixture. The materials react with water and the chemical products of the Portland cement to create a binder that holds concrete together. These include both newly produced materials such as calcined clays but also by-products and waste products such as fly ash from coal burning, ground granulated blast furnace slag from steel production, and ground glass pozzolan from waste glass. It is important to note that some SCMs, such as fly ash, are themselves by-products of industrial processes that produce high levels of carbon dioxide and other pollutants.

While none of these will completely replace Portland cement or offset carbon emissions, their utilization can significantly reduce the overall carbon footprint of concrete materials. Despite the existence of these alternatives, however, there is still a significant portion of concrete that is made without utilizing these technologies. For example, as of 2014, only 23 percent of worldwide cement usage was substituted with SCMs (which was only a modest increase of 3 percentage points from 2006). The slow rate of adoption of low-carbon concrete technologies happens for a few reasons: a lack of technical understanding of the technologies by designers and contractors, concerns about the cost of new or different materials, reluctance to take on risk associated with the new technologies by owners (e.g. municipalities, state agencies, federal agencies) and contractors, and a lack of support or funding to implement the new technologies from owners and contractors.[16]

Barriers to low-carbon concrete adoption: lack of technical understanding of new technologies, concerns about cost of new materials, reluctance to take on risk, and a lack of funding to implement new technologies.

Much of the resistance for adopting alternatives mixtures that have lower carbon footprints stems from the fact that no concrete mixture is the same, so there is no "one-size-fits-all" solution. Unlike other technologies, such as mobile phones, which can be mass produced using the same design and materials for each individual unit, concrete must be localized to each application. This is because the raw materials (such as gravel and sand), environmental conditions (like temperature and humidity), and strength requirements are different for each construction project, and even within individual projects. As such, we cannot create one "low-carbon concrete mixture" or formula that can be used everywhere. Engineers and contractors have to truly understand how to use alternative materials and owners have to take the risk of trying something new. This is a challenge that has persisted in the concrete and construction industries, resulting in slow acceptance of new technologies and materials. Policy initiatives can help address this problem by indicating the need for change and increasing support for these projects. This is important at not only the state and federal level, where funding incentives and requirements can shape projects, but at the local level, given the amount of projects that are managed by municipalities.

Local Policy Initiatives In the United States

Since 2019, several local initiatives implemented throughout the United States have encouraged the use of low-carbon concrete materials. In April of 2019, Honolulu, Hawaii, was the first municipality in the United States to pass a resolution encouraging the use of carbon sequestration in concrete;[17] a similar resolution passed shortly thereafter in Austin, Texas.[18] Those cities were joined by a resolution at the 87th annual meeting of the United States Conference of Mayors that called "upon its membership to prioritize utilizing post-industrial carbon dioxide mineralized concrete."[19] These measures show that local governments understand and generally support the need to reduce embodied carbon in concrete. However, such local resolutions have been relatively low impact due, in part, to the need for concrete plants to procure specialized equipment to implement CO_2 sequestration in concrete, which can be costly. Additionally, resolutions that encourage, rather than require or incentivize, new technologies can have limited impacts since they provide industry little motivation to change.

In 2020, the City of Portland, Oregon, introduced a new policy that requires Environmental Product Declarations (EPDs) for all concrete used in city projects.[20] EPDs report third-party verified environmental impact information for each concrete mixture, enabling the city to select lower-impact mixtures while maintaining performance. EPDs can be very useful because they distill complex environmental impact information into more accessible formats that can be compared across products. However, EPDs are often not created by smaller concrete plants because they can be expensive to create for the range of concrete mixtures that a company supplies.

Marin County in California similarly passed the Bay Area Low-Carbon Concrete Codes in 2020 that also requires EPD information.[21] This policy, perhaps the most rigorous to date in the United States, sets limits on the carbon emissions from and total cement used in concrete that is cast within the unincorporated areas of the county. The policy limits the total embodied carbon (as determined through an EPD) of a concrete mixture based on the required strength of the concrete. Higher required strengths are allowed to have higher embodied carbon, as generally strength is proportional to cement content. In cases where EPDs are not available, the policy then limits the total amount of Portland cement that can be used in a concrete mixture, based on the required concrete strength.

This policy provides extensive information on how to comply with the limits and provides exemptions in certain cases, but, in general, all construction must comply with the limits. Exemptions include instances in which low-carbon concrete systems are not available from any manufacturer, when the cost of meeting the policy requirements is “disproportionate to the overall cost of the project,”[22] and when compliance would impact the historic integrity of a building that is listed on local, state, or federal registers of historic buildings.

The thresholds on the allowable embodied carbon or cement content were also developed through an analysis that determined what were deemed achievable limits for certain types of concrete mixtures in the area. In order for this type of policy to be implemented elsewhere, however, a new analysis would need to be completed to determine attainable carbon reductions using locally available materials and conditions for each area of implementation.

These policy initiatives show the desire within communities to reduce the carbon footprint of their concrete infrastructure and, when implemented, can result in a significant reduction of CO_2 emissions. However, the format of such policies tends to either encourage particular technologies for achieving lower carbon emissions or require significant financial investments either by the community or local concrete businesses. The Village of Hastings-on-Hudson in New York has, however, developed an alternative approach to the decarbonization of concrete.

A retaining wall replaced by the Village of Hastings-on-Hudson using low-carbon concrete.

Photo courtesy of Ion Simonides.

A Case Study: The Hastings Resolution

In May 2020, the Village of Hastings-on-Hudson in the town of Greenburgh, New York, passed its own concrete resolution.[23] Unlike similar policies adopted in other localities across the United States, it does not set specific requirements on global warming potential reduction or encourage the use of specific technologies. Instead, it supports the use of *any* technology that may reduce the carbon footprint of concrete made for the village.

The resolution stated that:

> *"the Village of Hastings-on-Hudson encourages, and will work to promote, the use of low embodied carbon concrete products in building and infrastructure projects involving concrete, where the utilization of low embodied carbon concrete does not significantly increase the costs of or delay project completion, and where utilization does not compromise either construction integrity or public safety. Such promotion could include, but may not be limited to, identifying local low embodied carbon concrete product options, making embodied carbon concrete educational materials more accessible, recognizing local projects utilizing low embodied carbon concrete products, and sharing Hastings-on-Hudson's program successes and lessons learned with other towns and local governments in the state and region."*[24]

The resolution is quite broad compared to the policies discussed above, allowing for significant flexibility and staged implementation of low-carbon concrete technologies. According to the mayor of Hastings-on-Hudson, Nicola Armacost, the resolution was based off of the Honolulu and Austin resolutions but with "our own special twist."[25] While its breadth lacked specific requirements or incentives, in this case by not limiting the type of technology supported, the resolution also worked to encourage contractors and town engineers to utilize the broad range of technologies available to them, rather than focusing on those which may be higher in cost, not available to them, or not practical for particular infrastructure projects that their village may pursue. The inclusion of educational initiatives also means that the village has a charge to be supportive of working with outside groups to develop the knowledge required to use these solutions and promote them locally and elsewhere.

At least as consequential as the language of the resolution itself, was the collaborative work between the village and other stakeholders that went into its development and followed from its passage. Work on the resolution began in January 2020 through a collaboration between Mayor Armacost, Chris Neidl, and Ion Simonides. Neidl is the founder of the OpenAir Collective, an all-volunteer grassroots organization whose mission is to advance carbon capture and reduction technologies around the globe. Simonides, a member of the OpenAir Collective and a resident of Hastings-on-Hudson, was particularly interested in helping to develop this legislation because it would benefit his own hometown and the resolution could possibly be used as a roadmap for other municipalities to adopt low-carbon concrete procurement policies. Simonides led the writing of the resolution and used the connections in the OpenAir Collective to answer technical questions and get advice on what may work best. Mayor Armacost noted that the combination of a motivated constituent, an elected official behind the resolution, and the ability to crowdsource knowledge from the OpenAir Collective members was the "serendipity, luck, and magic"[26] that enabled the development and passage of the resolution in less than six months.

While passage of the resolution was fast, it did not come without questions and concerns. Village trustees were supportive of the idea but were concerned about greenwashing (i.e., having a resolution that sounded sustainable but didn't actually result in change). The trustees and the town engineer were also concerned about the quality of the material, particularly with respect to strength and durability. Finally, there were logistical concerns about being able to source low-carbon concrete materials locally, especially as the village trustees wanted to ensure that carbon reductions would not be canceled out by transportation emissions. Simonides and the support of the OpenAir Collective were integral to answering these questions, according to Mayor Armacost. The access to a broad organization of people that could provide accurate data and information allowed for quick resolutions to the concerns of the trustees and other stakeholders.

The language of the resolution focuses on "encouraging" technologies rather than requiring or incentivizing their use. While this language is not strong in legislative terms, the effectiveness of the resolution appears to be derived from the manner in which it was enacted. Mayor Armacost, Neidl, and Simonides worked with the trustees and other stakeholders to assuage concerns about the resolution prior to introducing it for a vote. They made sure the concept of low-carbon concrete was technologically viable, economically feasible, and locally available. Ultimately, the early collaboration among stakeholders not only enabled the passage of the resolution but allowed Hastings-on-Hudson to then move quickly when procuring low-carbon concrete for a construction project shortly after the resolution was passed.

The early collaboration among stakeholders not only enabled the passage of the resolution but allowed Hastings-on-Hudson to then move quickly when procuring low-carbon concrete for a construction project shortly after the resolution was passed.

The first project in which the goals of the resolution were implemented—the replacement of a concrete retaining wall that had been damaged in an accident involving a large truck—was completed in the summer of 2020. Simonides worked with the village engineer to determine if they would be able to procure a low-carbon concrete mixture. When they first approached the concrete supplier and asked for "green concrete," they were met with confusion. The supplier had not specifically been asked to provide low-carbon concrete before and was unsure what would meet that requirement. Fortunately, the concrete producer had already developed a concrete mixture that replaced 20 percent of the Portland cement with ground granulated blast furnace slag, a waste product of the steel making industry that would otherwise be landfilled if not used in concrete.[27] The producer was using it because of its beneficial impact on strength and durability in concrete but had never considered it as a mixture that could also be classified as having a lower-carbon impact. Data from the producer showed that this low-carbon concrete mixture met the strength requirements needed for the wall, and the project was successfully completed using that mixture.

With a successful pilot project completed, the village is now looking toward more ambitious projects. A new elementary school is being designed using low-carbon concrete and a large sidewalk project with the neighboring Village of Dobb's Ferry is being planned that will utilize low-carbon concrete. The sidewalk project is also a part of the OpenAir Collective's new Open-Source Sidewalk initiative. This program is working with communities to help them develop and find low-carbon concrete mixtures that can be used on sidewalk projects. The goal is to have a large database of concrete mixtures from around the country that municipalities can use as a starting point for their own low-carbon concrete projects. Additionally, the village has made updates to the Hastings Green Building Code that allows for and encourages the use of low-carbon concrete in building projects that are currently awaiting approval of the revised document from the State of New York.

Beyond the Village

Outside of the Village of Hastings-on-Hudson, the low-carbon concrete resolution is having an impact in surrounding communities and at the state level. The Village of Ardsley passed a similar resolution promoting the use of low-carbon concrete and the Village of Dobb's Ferry is considering doing the same. New legislation, known as the Low Embodied Carbon Concrete Leadership Act (LECCLA), has been proposed in both New Jersey and New York with multiple sponsors in each state's assembly and senate.[28] There are initiatives in support of LECCLA-like policies being organized by stakeholders and advocates in Virginia (as well as in the United Kingdom) to introduce similar legislation. These pieces of legislation have been able to use the Hastings resolution as an example for how this type of program can be successful while incorporating some more specific requirements and potential incentives. Not coincidentally, they are also being led by the grassroots volunteer members of the OpenAir Collective, which collaborated on the development of the Hastings resolution and pushed for the introduction of both the LECCLA bills in New York and New Jersey.

If enacted, the LECCLA legislation could work to promote and support the use of low-embodied carbon concrete materials in publicly procured infrastructure projects across a given state. The bill introduced in New York passed both houses of the legislature in June 2021. If signed and enacted into law, that legislation would direct the state to establish a low-carbon concrete standard that would apply to all concrete contracts with state agencies and departments. During the standard design and rulemaking process, the state is directed to evaluate the potential implementation of a "climate competition" incentive for concrete producers. Such a system would apply an artificial discount to the price of construction bids that attain and demonstrate superior climate performance (or "global warming potential") for mixes via third-party EPDs. The current New Jersey legislation, which was reported out of committee in May, would direct the state to implement such a discount rate directly through the legislation. This approach is designed to help offset some of the start-up costs associated with procuring EPDs and understanding new technologies.

Conclusions

The need for reducing the carbon emissions associated with concrete has long been a topic of discussion within the construction industry and relevant public offices, and over the past two decades many options have been researched to address this issue. While there is still much work to be done in addressing the problem from a technological standpoint, a lack of industry and broader public measures to encourage acceptance and uptake has significantly hindered the implementation of lower-impact concrete materials. Until recently, there has been little movement within the United States to develop policy that promotes these new technologies. Understanding how some municipalities have found success in addressing the climate impact of their construction activities, and how those successes might be translated at the state or federal level, is helpful for implementing policies more broadly. As reflected here, policies that offer some flexibility across geography, projects, and funding, appear to have benefits in assuring implementation. So, too, does the early development of working groups that can bring stakeholders together before policies are solidified.

As we observe low-carbon concrete policies beginning to be enacted at the state and federal level, further questions might address how to support those types of concrete-based projects and methods that can offer the biggest reductions in carbon impacts at larger scales. This will be an ongoing task and more research and discussion are needed to understand how best to approach the daunting task of combating climate change with respect to the construction and maintenance of infrastructure. It is clear, however, that some local governments are beginning to take up the challenge.


ENDNOTES

Endnotes

1 The White House, "FACT SHEET: The American Jobs Plan," news release, May 4, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/.

2 Ibid.

3 Karen L. Scrivener, Vanderley M. John, and Ellis M. Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry," *Cement and Concrete Research* 114 (December 2018): 2-26, https://doi.org/10.1016/j.cemconres.2018.03.015.

4 Sabbie A. Miller, et al., "Greenhouse gas emissions from concrete can be reduced by using mix proportions, geometric aspects, and age as design factors," *Environmental Research Letters* 10 (November 12, 2015), https://iopscience.iop.org/article/10.1088/1748-9326/10/11/114017/meta.

5 Steven H. Kosmatka and Michelle L. Wilson, *Design and Control of Concrete Mixtures: 16th Edition* (Skokie, IL: Portland Cement Association, 2016).

6 Miller et al., "Greenhouse gas emissions from concrete can be reduced by using mix proportions, geometric aspects, and age as design factors."

7 Harvey, Chelsea, "Cement Producers Are Developing a Plan to Reduce CO_2 Emissions," *Scientific American*, July 9, 2018, https://www.scientificamerican.com/article/cement-producers-are-developing-a-plan-to-reduce-co2-emissions/.

8 Scrivener, John, and Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry."

9 Paulo J. M. Monteiro, Sabbie A. Miller, and Arbad Horvath, "Towards sustainable concrete," *Nature Materials* 16 (July 2017): 698-9, https://doi.org/10.1038/nmat4930.

10 G. P. Hammond and C. I. Jones, "Embodied Energy and Carbon in Construction Materials," *Proceedings of the Institution of Civil Engineers-Energy* 161 (2008): 87-98, https://doi.org/10.1680/ener.2008.161.2.87.

11 Scrivener, John, and Gartner, "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry."

12 Ibid.

13 "Concrete CO_2 Fact Sheet," National Ready-Mixed Concrete Association (NRMCA), June 2008, https://www.greenconcrete.info/downloads/11_ConcreteCO2.pdf.

14 Sabbie A. Miller and Frances C. Moore, "Climate and health damages from global concrete production," *Nature Climate Change* 10 (May 2020): 439-43: https://doi.org/10.1038/s41558-020-0733-0.

15 Kosmatka and Wilson, *Design and Control of Concrete Mixtures: 16th Edition*.

16 Wofram Schmidt, Mark Alexander, and Vanderley John, "Education for sustainable use of cement based materials," *Cement and Concrete Research* 114 (December 2018): 103-14, https://doi.org/10.1016/j.cemconres.2017.08.009.

17 City Council of Honolulu, Hawaii, "Requesting the City Administration to Consider Using Carbon Dioxide Mineralization Concrete for All Future City Infrastructure Projects Utilizing Concrete," Council Resolution 18-283, December 3, 2018, http://www4.honolulu.gov/docushare/dsweb/Get/Document-212511/RES18-283.pdf.

18 City of Austin, Texas, "Low Carbon Concrete for City for Construction Projects," Environmental Commission Motion 20190619 007c, June 19, 2019, http://go.carboncure.com/rs/328-NGP-286/images/City%20of%20Austin%20-%20Low%20Carbon%20Concrete%20Recommendation%2020190619.pdf.

19 United States Conference of Mayors, "Urging all cities to consider using carbon dioxide mineralized concrete for future city building and infrastructure projects utilizing concrete," from Resolutions of the 87th Annual Meeting, 2019, https://www.usmayors.org/the-conference/resolutions/?category=a0D4N00000FDDPaUAP&meeting=87th%20Annual%20Meeting".

20 City of Portland Office of Management and Finance, Oregon, "Notice of New Requirements for Concrete," May 15, 2019, https://www.portlandoregon.gov/brfs/article/731696.

21 "Bay Area Low-Carbon Concrete Codes Project," County of Marin, accessed June 9, 2021, https://www.marincounty.org/depts/cd/divisions/sustainability/low-carbon-concrete-project.

22 Ibid.

23 Village of Hasting-on-Hudson, New York, "Resolution for Low-Embodied Carbon Concrete for Building and Infrastructure Projects in the Village of Hastings-On-Hudson," May 20, 2020, https://www.hastingsgov.org/sites/g/files/vyhlif3241/f/uploads/20_green_concrete_resolution_signed.pdf.

24 Ibid.

25 Nicola Armacost (mayor of Hastings-on-Hudson, New York), interview with the author, March 12, 2021.

26 Ibid.

27 Chiu Chen Onn, et al., "Strength, Carbon Footprint and Cost Considerations of Mortar Blends with High Volume Ground Granulated Blast Furnace Slag," *Sustainability* 11, 24 (2019): 7194, https://doi.org/10.3390/su11247194.

28 "Low Embodied Carbon Concrete Leadership Act (LECCLA)," OpenAir Collective, https://openaircollective.cc/leccla.

ABOUT THE ROCKEFELLER INSTITUTE

Created in 1981, the Rockefeller Institute of Government is a public policy think tank that conducts cutting-edge, nonpartisan research and policy analysis. Our mission is to improve the capacities of communities, state and local governments, and the federal system to work toward genuine solutions to the nation's problems. Through rigorous, objective, and accessible analysis and outreach, the Institute gives citizens and governments facts and tools relevant to public decisions.

Learn more at www.rockinst.org.

LEARN MORE

www.rockinst.org

@rockefellerinst

Rockefeller Institute of Government