Concrete Solutions Guide

Six Actions to Lower the Embodied Carbon of Concrete

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About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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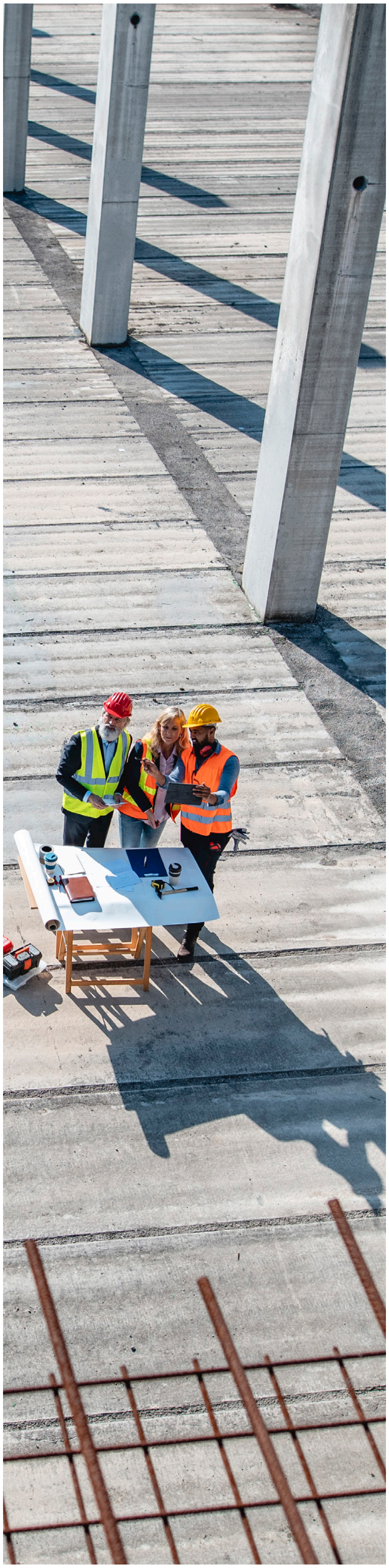

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Executive Summary

The demand for low-embodied-carbon concrete is growing rapidly. This transition is taking place in parallel with a growing network of policy frameworks across the United States that regulate the carbon intensity of building materials.[1] It also comes at a time when industrial firms are quickly recognizing the importance of aligning their business models with the urgencies of climate change and the goals of the Paris Agreement.

This guide provides a user-friendly overview of proven and scalable solutions to reduce concrete's contribution to climate change. Most all of the solutions described here are market-ready—the result of decades of research and real-world trials. In addition to helping advance the environmental goals of concrete purchasers, these solutions also offer opportunities for producers to reduce costs and establish a leadership role within a changing industry.

The ***Concrete Solutions Guide*** highlights six key opportunities to reduce embodied carbon in concrete products without compromising financial or material performance:

1. **Know Your Numbers: Performance-Oriented Specifications**
   The industry status quo—using prescriptive specifications for the composition of concrete mixes—limits producers' ability to innovate with low-carbon, high-performance solutions. Replacing mix requirements with performance-oriented specifications can foster innovation in low-carbon concrete without compromising performance or safety.

2. **Mix It Up: Supplementary Cementitious Materials (SCMs)**
   Concrete producers can reliably substitute approximately 40% of traditional inputs with low-carbon alternatives, including fly ash, ground glass, and others.[i] In the United States alone, increased deployment of SCMs could save 27 megatons of carbon dioxide equivalent (Mt CO_2e) every year from current levels[ii]—roughly equal to taking 5.9 million cars off of American roads.

[i] Based on RMI analysis of USGS data for cement and slag production and ACAA data for fly ash production, as well as substitution limits set by ASTM C595. Estimates assume that all fly ash and slag can be processed to a suitable grade.
[ii] Based on RMI analysis of USGS cement kiln fuel consumption data using EPA emissions factors and EGrid data. Resource consumption for cement and SCMs based on R. Feiz et al., "Improving the CO_2 Performance of Cement, Part I: Utilizing Life-Cycle Assessment and Key Performance Indicators to Assess Development within the Cement Industry," *Journal of Cleaner Production*, vol. 98 (2015): 272–281; and C. Heidrich, I. Hinczak, and B. Ryan, "SCM's Potential to Lower Australia's Greenhouse Gas Emissions Profile," Australasian Slag Association Conference, Sydney, 2005.

3. **Plug and Play: Sensors Can Save Time, Money, and Materials**
   Instead of using overdesign calculations that lead to unnecessarily high cement contents in mixes, digital sensors can log concrete temperature and strength on-site. This technology reduces guesswork, limits the possibility of structural failure, and reduces embodied carbon.

4. **Embrace Circularity: Concrete Recycling**
   Using recycled concrete aggregate (RCA) can offer up to 50% cost savings compared to natural aggregate. This recycling greatly reduces the volume of new material required for nonstructural applications, such as base layers for roads, with significant savings for project-level embodied carbon.

5. **Carbon as a Service: Sequestering CO_2 in Concrete**
   CO_2 can be directly mineralized in concrete affordably, which offers co-benefits in concrete strength and opens a wide field of possibilities that place concrete at the center of creative climate solutions. While this technology is the least mature of those covered in this guide, it is likely to play an important role in future innovations.

6. **Use Green Heat: Decarbonize Kiln Technology**
   By increasing the use of biomass where available and making simple efficiency upgrades, the embodied carbon in cement could be reduced by approximately 18% without retiring existing capital infrastructure.[2]

Although these solutions are relatively straightforward, the cement and concrete value chain features a complex network of stakeholders. Every actor has an opportunity and a role to play in lowering the embodied carbon of concrete. The solutions in this guide will be useful for concrete producers and cement manufacturers, as well as developers, designers, contractors, and policymakers. Critically, this information is intended to foster relationships in sustainable procurement between these stakeholders and to advance synergies in climate-conscious innovation. Readers may find the solutions most relevant to their background by referencing the boxes below.

1 Know Your Numbers: Performance-oriented specifications

2 Mix It Up: Supplementary cementitious materials (SCMs)

3 Plug and Play: Sensors can save time, money, and materials

4 Embrace Circularity: Concrete recycling

5 Carbon as a Service: Sequestering CO_2 in concrete

6 Use Green Heat: Decarbonize kiln technology

Recommended Solutions for Key Stakeholders in the Cement-Concrete Supply Chain

Concrete producers bring deep technical expertise to mix and deliver concrete, but they need a market signal to expand the availability of low-carbon products.

Solutions: 2 3 5

Cement manufacturers operate kilns with decades-long service lives, which account for the majority of the embodied carbon in concrete. Process innovations can lower the embodied carbon of cement without disrupting existing kiln infrastructure.

Solutions: 2 6

Developers hold the power of the purse in construction and infrastructure. They are keen to responsibly manage project costs, but also recognize that a climate-conscious building delivers value for the planet and the public.

Solutions: 1 4 5

Designers work in engineering firms and government agencies, such as departments of transportation. They create specifications and guidance for the built environment and are responsible for maintaining safety and usability.

Solutions: 1 2 4

Contractors bring designs to life and often carry a large burden of risk, from the safety of their staff to the project budget. The solutions in this guide have been vetted by RMI staff and members of the building industry to ensure that they do not compromise safety or cost.

Solutions: 3 4 5

Policymakers can have tremendous impact in lowering the embodied carbon in concrete by pursuing clean procurement policies and updating building codes. This guide focuses on solutions that can be implemented without policy interventions, but, where applicable, it also identifies avenues by which policymakers can support market transformation.

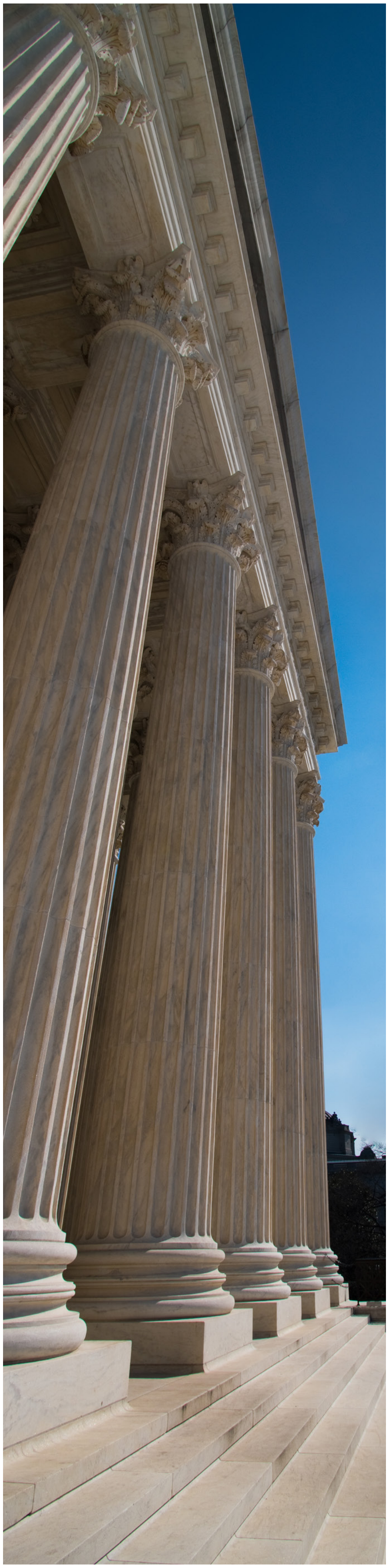
Solutions: 1 2 3 4 5 6

Background

More than one-quarter of the greenhouse gas emissions from the global building sector are in embodied carbon.[3] These emissions arise from the manufacture, transportation, installation, maintenance, and disposal of materials that are used in construction, such as steel, wood, and concrete.[4] Of these, concrete has the greatest impact on global climate change, narrowly beating out steel. The embodied carbon in concrete comes primarily from the manufacture of cement, which is the main binding agent and most expensive ingredient in concrete. Cement production alone generates 8% of global greenhouse gas emissions;[5] for this reason, embodied carbon has preoccupied the cement and concrete industry for decades.

Beginning in the 1990s, engineers and designers have reckoned with the high carbon intensity of cement.[6] Over the ensuing years, materials scientists, industrial engineers, and policymakers have designed various approaches to reduce the embodied carbon of concrete, often saving costs at the same time. More recently, this effort has accelerated significantly. Industrial sectors across the globe are looking for pathways to decarbonize on a time frame that aligns with the science-based targets called for in the Paris Agreement. With the support of consumers who increasingly seek out low-carbon products, stakeholders around the world are designing decarbonization roadmaps, while low-carbon procurement policies emerge in a growing number of jurisdictions.

This shifting landscape poses a challenge and an opportunity to the cement and concrete industry, which thus far has primarily pursued incremental emissions reductions. Given the cost, risk, and durability of concrete infrastructure, stakeholders are understandably cautious about adopting new practices. Even when different members of the concrete value chain support efforts to lower embodied carbon, the large number of actors involved in building procurement and construction poses a unique challenge to creating consensus around reforming best practices.



A Note on Policy

This guide seeks to bridge the information gap by improving the visibility of scalable and tested products, practices, and technologies that can lower embodied carbon at or near cost parity. Although policy can play a critical role in accelerating the diffusion of these practices, the solutions detailed here do not require modifications in building codes or other action by government. Rather, these approaches can be achieved by market-driven innovation among key stakeholders who are active in the design-build process.

Even so, a robust policy landscape that encourages innovation (such as the recent code improvements in Marin County, California, and low-carbon purchasing policy in Portland, Oregon) have the potential to encourage broader uptake of these solutions. By employing the solutions found within the guide, private-sector actors stand to benefit by keeping ahead of regulation; at the same time, their foresight will build reputational capital and improve their social license to operate. These early adopters in the buildings sector will take a leading role in the movement to reduce the embodied carbon of materials at a time when climate change is reshaping how buildings and infrastructure function within societies. For more on the policy innovations in low embodied carbon spreading across the United States, please see the **resources section** at the end of this guide.

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CONCRETE SOLUTIONS GUIDE

Know Your Numbers

Performance-Oriented Specifications

Performance-oriented specifications are an alternative to existing standards that dictate the mix proportions of concrete. Instead of stipulating the ratio or types of inputs to a concrete mix like prescriptive requirements, performance-oriented standards require that the concrete product meet certain thresholds (e.g., for strength), without specifying how those standards must be achieved. Moving toward more performance-oriented specifications can diffuse the perceived tension between embodied carbon and performance.

Key Takeaways

Some limitations to using low-carbon concrete are policy-based (e.g., building codes and concrete mix specifications), but communication and coordination between designers and concrete producers early in the design process can offer avenues to navigate these constraints.

Policymakers should work closely with industry stakeholders and support performance-oriented specifications in building codes wherever possible.

When developers or designers orient specifications around performance, they allow concrete producers to innovate, inviting low-embodied-carbon products to replace traditional mixes.

Opportunity

Concrete producers have continued to innovate specialized blends, developed in partnership with clients seeking to improve environmental performance. These projects succeed where performance-oriented specifications allow experts to apply creative solutions, while minimizing unnecessarily prescriptive requirements that constrain the concrete space. Developers have the opportunity to expand the benefits of performance, cost savings, and sustainability that innovative concrete blends can bring to projects by encouraging the use of performance-oriented specifications in the early stages of project development.

Concrete specifications often focus on mixture composition, restricting the ability of producers to create innovative mixes with lower embodied carbon and high performance. The National Ready Mix Concrete Association (NRMCA), a peer-to-peer initiative, also supports the transition toward more performance-oriented specifications. A survey conducted by the NRMCA found that prescriptive specifications are often characterized by a combination of the following requirements: 1) restrictions on supplementary cementitious material (SCM) quantity, 2) maximum water-to-cement ratio, 3) minimum cementitious content, 4) restrictions on SCM type, and 5) restrictions on aggregate grading.[7]

But high-quality concrete does not require rigorous specifications on mix type. The American Concrete Institute's standards, for instance, do not feature many of the input-based specifications used today. These prescriptive specifications unintentionally limit the ability of manufacturers to provide low-carbon concrete by narrowing the solution space and discouraging innovation.

Although concrete producers cannot prevent the use of prescriptive specifications, they can take steps to accelerate the transition to performance-oriented specifications. For instance, producers can provide customers with examples of alternative mixes with lower carbon footprints that meet the performance requirements of a particular project. Educating consumers will help expand market reach while improving the visibility of a product and delivering greater value to customers who are eager to reduce embodied carbon.

Designers in turn have a responsibility to remove stringent and unnecessary prescriptive requirements where possible, though prescriptive requirements can still play an important role in project development. Leveraging lived experience through understanding local material supply or particular site conditions can direct concrete producers to the most fertile ground for mix innovation.

Related Solutions

2. Mix It Up: Supplementary Cementitious Materials (SCMs)

3. Plug and Play: Sensors Can Save Time, Money, and Materials

4. Embrace Circularity: Concrete Recycling

5. Carbon as a Service: Sequestering CO_2 in Concrete

Considerations

Specifications in building design always prioritize safety. This is a sizable challenge, as procedural changes in government procurement can take years. Designers will often specify a concrete blend based on familiarity, potentially resulting in an overreliance on traditional blends with higher embodied carbon content. In turn, developers want to mitigate risk, and they often follow the specification of designers without question. Finally, concrete producers, who have the most sophisticated understanding of the science and performance of concrete, are often excluded from this process and are only involved to deliver a specified product. Addressing this systemic issue requires improving communication across the value chain, with an emphasis on early engagement about the potential of using performance-oriented specifications to reduce embodied carbon.

State of the Market

Several resources for specifying performance characteristics have been developed in recent years. *The Guide to Improving Specifications for Ready Mixed Concrete* by the National Ready Mixed Concrete Association is one such resource. This guide and other references for developing performance-oriented specifications can be found in the **resources section** at the end of this guide.

Public agencies and departments of transportation can also encourage uptake of performance-oriented specifications. This is a sizable challenge, as procedural changes in government procurement can take years. Even so, several large government agencies are already deploying performance-oriented specifications, including the Federal Highway Administration and the Port Authority of New York and New Jersey.[8]

2

Mix It Up

Supplementary Cementitious Materials (SCMs)

Substituting cement with supplementary cementitious materials (SCMs)—such as fly ash, ground glass, natural pozzolans, and blast furnace slag—creates an opportunity for cost-effective decarbonization. These waste and by-product components can be mixed into concrete, preserving performance while reducing the need for cement. Portland cement is responsible for 90% of the total embodied carbon of concrete;[9] reducing this input offers one of the most effective avenues for creating more sustainable concrete. Substitution often repurposes waste materials and is a cost-competitive intervention in many instances.

Key Takeaways

Up to 40% substitution of cement with SCM is possible based on individual mix limits and supply across the United States,[iii] offering potential savings of 27 Mt CO_2e per year.[iv]

Substitution can deliver up to 80% emissions reductions for a given application.[v]

Using SCMs can reduce the cost of the cement blend by up to $45/ton.[vi]

The availability of SCMs may diminish in the future, potentially requiring the development of new sources (e.g., reclaiming stored fly ash or mining natural pozzolans).

The primary barriers to increasing SCM use are prescriptive specifications, unfamiliarity from industry, and supply-side restrictions.

Opportunity

Both cement and concrete producers have opportunities to use alternative materials. Cement producers may produce blended cements (defined in ASTM C595), particularly portland limestone cement (PLC or Type 1L). Raw ground limestone acts as a seed crystal to enhance the cement hydration.

Concrete producers can also use a variety of SCMs to lower embodied carbon while meeting specifications. These include:

- Waste or by-product pozzolans such as fly ash and ground glass, which are mostly silica
- Natural pozzolans, such as volcanic ash, which perform similarly to waste pozzolans
- Ground granulated blast furnace slag (GGBFS), a by-product of steelmaking that contains calcium and silica, and that can almost entirely replace portland cement (up to 95% in ASTM C595)

These strategies can also be combined to further reduce embodied carbon. For example, a ready-mix operator could start with a portland limestone cement base and combine it with fly ash or GGBFS. The additional reductions in embodied carbon are complemented by improved strength and durability.[10]

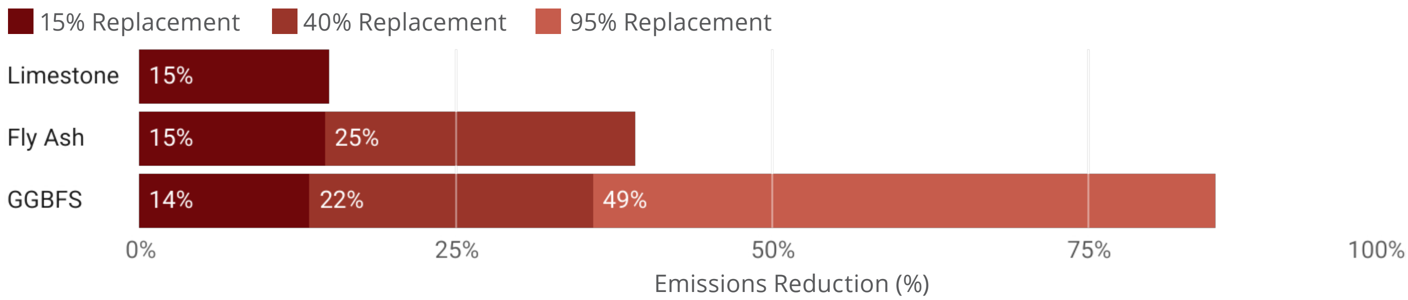
Because SCMs have low embodied carbon relative to cement, substitution translates into steep emissions reductions, potentially in excess of 80% (see Exhibit 1).

[iii] See footnote i on page 5.
[iv] See footnote ii on page 5.
[v] See footnote ii on page 5.
[vi] Based on USGS and BLS data for raw material and transport pricing. Results are consistent with McKinsey global pricing estimates: **https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement.**

Substitution Limits

Given the different chemistry of the materials and subsequent impacts on concrete properties (e.g., strength or workability), the ASTM C595 standard sets out different substitution limits for limestone, pozzolans, and GGBFS at 15%, 40%, and 95%, respectively.

Exhibit 1: Emissions reductions in cement blends using SCMs



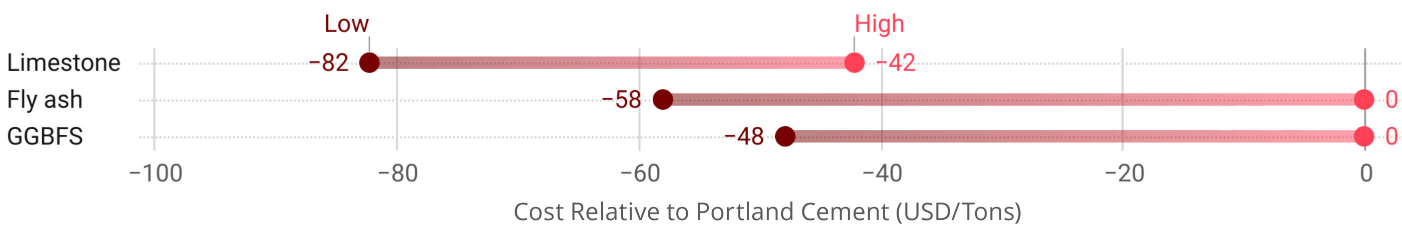
Emissions reductions for each type of SCM are dependent on the SCM's embodied carbon and the substitution limit. All of the SCMs have significantly lower embodied carbon than cement resulting in steep emissions reductions. Fly ash and limestone have almost no embodied carbon resulting in emissions reductions roughly equivalent to the substitution limit. There is a small amount of emissions associated with the processing and transport of GGBFS but the higher substitution limits for this material allows for large emissions reductions. Colors are the substitution limits. Values written on the bars are the emissions reductions.

Cost

The price of each material varies regionally, with most costs incurred through transportation. As a result, SCMs can be cheaper than portland cement in locations close to a source. In some cases, a concrete mix containing SCM can be produced at a ready-mix facility without additional capital costs beyond additional storage capacity.

As shown in Exhibit 2, for areas with a close source of SCM, this process innovation can offer significant cost savings compared with portland cement. For concrete producers farther from SCM sources, the cost difference is negligible.

Exhibit 2: Variation in SCM cost is mostly associated with required transport distance

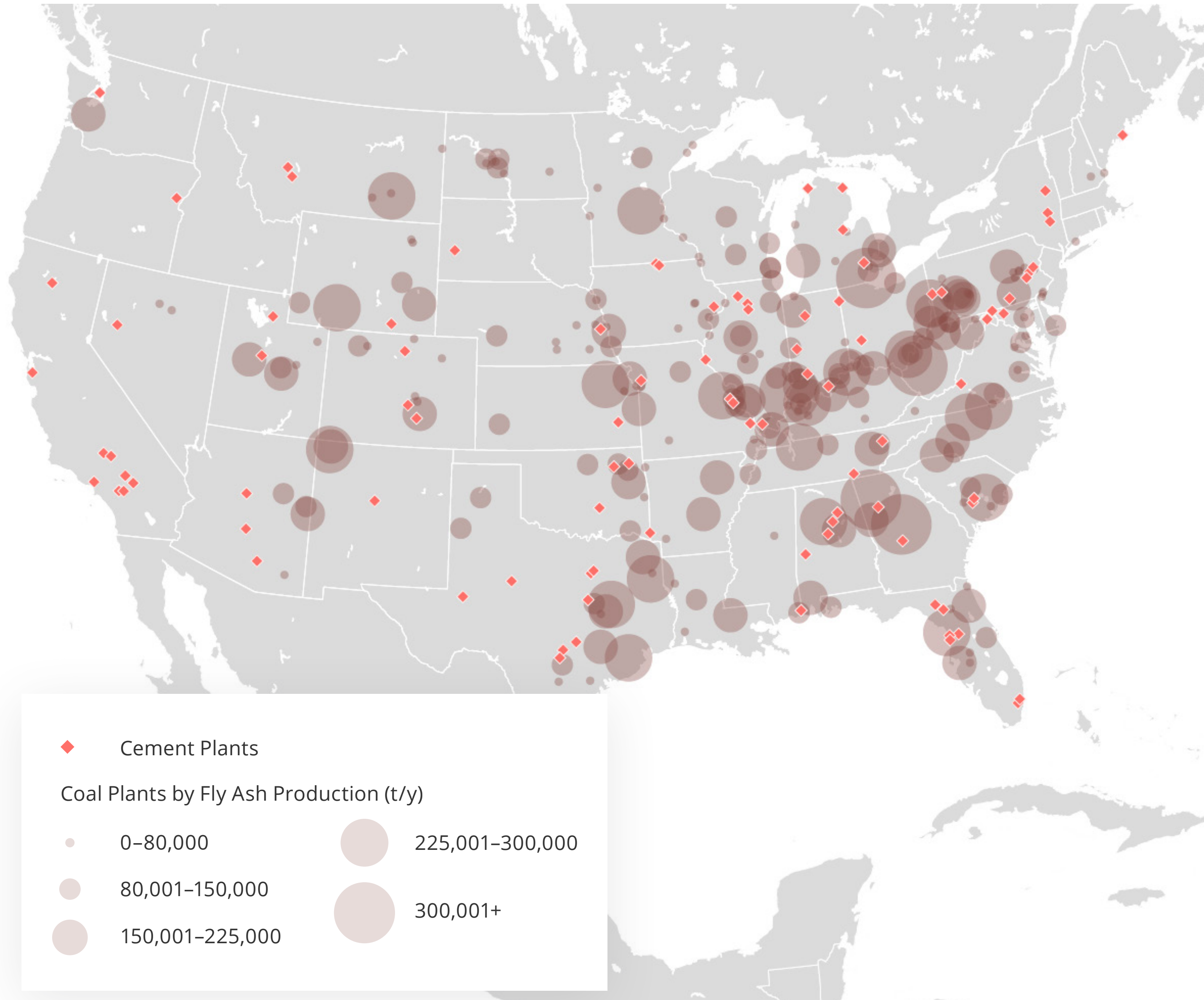


SCM costs are highly dependent on location. As result, there is a significant range of prices. In almost all places where an SCM can be sourced it will be less expensive than cement.

Considerations

Barriers to further adoption of SCMs include prescriptive specifications and a lack of familiarity with options (e.g., natural pozzolans and ground glass). But the greatest hurdle is the complicated supply-side dynamics of connecting concrete manufacturers with SCMs.

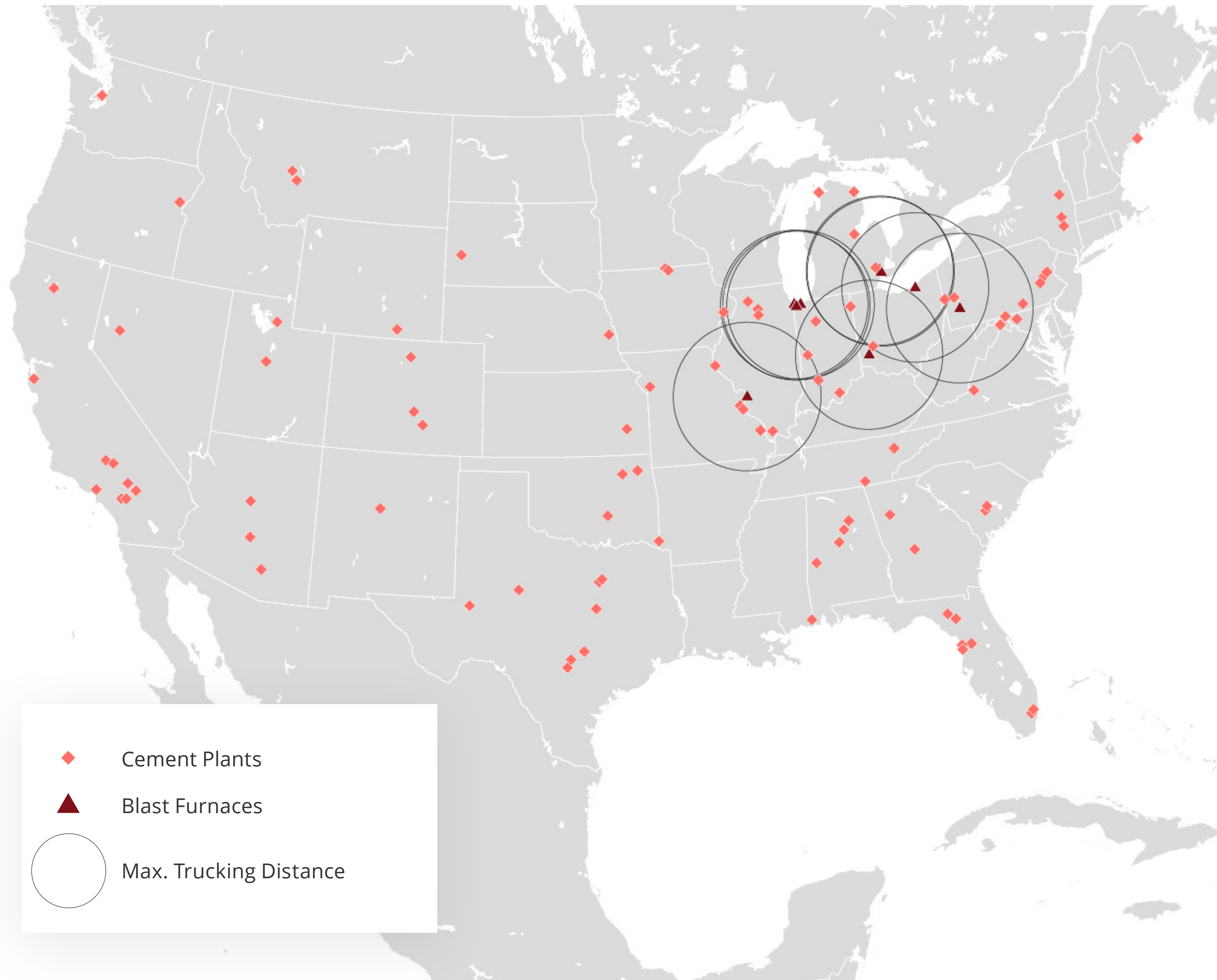
Exhibit 3: Fly ash supply is limited in the West



Fly ash is a byproduct of coal-fired power plants. As coal power is phased-out, fly ash availability will be constrained. This is already the case in the West where there are few coal-fired power stations producing fly ash in any significant quantity.

The overall ratio of SCMs in concrete mixes is limited to roughly 40% due to concrete quality considerations as well as material supply.[vii] This estimate of potential overall substitution is based on the ASTM C595 limit for limestone (15%) and current US production of both fly ash (27 Mt/y based on ACAA data) and GGBFS (8 Mt/y based on USGS data).

Exhibit 4: GGBFS is only produced in the Great Lakes Region



GGBFS supply is even more constrained geographically than fly ash. The last remaining blast furnaces are located in the Great Lakes region and the maximum trucking distance (for a breakeven price with cement) further limits the area in which this SCM can be used.

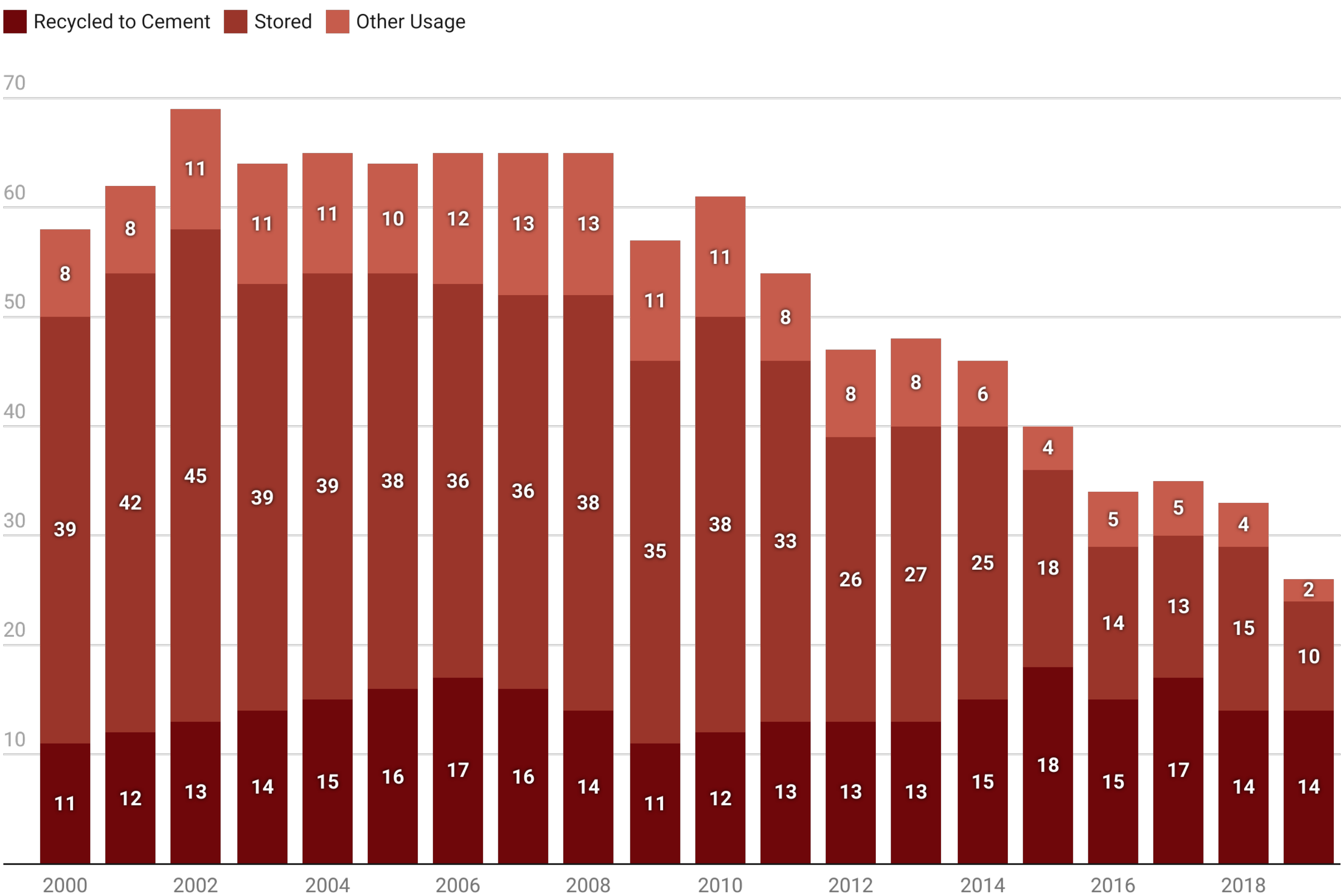
[vii] Based on USGS data for cement production (https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf) and GGBFS (**https://www.usgs.gov/centers/nmic/iron-and-steel-slag-statistics-and-information**) and ACAA data for fly ash consumption (**https://acaa-usa.org/publications/production-use-reports/**).

For concrete producers, incorporating SCMs requires securing a reliable supply.

- Limestone: Although cheap and widely available, the use of limestone is limited to 15% in ASTM C595. The inclusion of limestone will primarily occur in blended cement, as it is already available to cement producers as a raw feed material for the kiln.

- Fly ash: New supply of fly ash will continue to decline with the retirement of coal-fired power stations, and as emissions regulations lead to ash with a high carbon content. New supply could be developed by reclaiming fly ash from legacy storage ponds. Current US fly ash production is below the maximum possible substitution rate in a concrete mix (40%). Finally, this maximum rate is not suitable for certain concrete applications (e.g., those requiring rapid early strength gain).[11]

Exhibit 5: Stored fly ash could represent a significant opportunity (million tons)



A large amount of fly ash has been stored across the United States over the past 20 years. As new fly ash production decreases (owing to the phase-out of coal-fired power), this stored material could be reclaimed and used in concrete production.

- GGBFS: The supply of furnace slag is limited to the Midwest, where blast furnaces are still in operation. Given its higher material cost, furnace slag can only be economically transported over relatively short distances (roughly 300 km). While the substitution limit, at 95%, is high in terms of the amount of GGBFS that can be incorporated into a concrete mix, the overall material supply is low at 3 Mt/y.[viii] This supply rate could potentially expand to 8 Mt/y through the installation of granulation facilities at all blast furnaces. However, this would still only amount to 8% of the total 102 Mt of annual cement demand in the United States. GGBFS imported from overseas is also available in coastal regions, but the emissions associated with shipping decrease net reductions in embodied carbon.

At present, fly ash presents the best opportunity for overall abatement, given the balance between substitution limits and material availability. Although the amount of fly ash used in cement has remained stable, overall production has reduced significantly as coal-fired power stations are retired. This trend will continue, with production expected to drop below current fly ash usage sometime between 2025 and 2035.

However, data from the American Coal Ash Association indicates that over the past 20 years, 600 Mt of fly ash were stored in various waste sites. Recovery of this fly ash could provide US concrete producers with 14 years of SCM at the highest substitution rate—40%—while providing a separate revenue stream to fund rehabilitation and closure costs once a coal-fired power station is shut down. Several promising studies have been completed on the feasibility of reclaiming stored fly ash as a new source of SCMs to mitigate cement emissions.[ix] Boral has published a case study from Washingtonville, Pennsylvania, where approximately 2 Mt of fly ash generated in the 1980s and 1990s are being reclaimed for use in concrete.[12]

The use of fly ash in concrete may also reduce some nonclimate environmental impacts of fly ash storage. An EPA analysis found that the environmental releases from concrete containing fly ash were comparable to or lower than those from ordinary concrete.[13] At the same time, the use of fly ash reduces the need to impound these materials in surface ponds, which are known to spill and contaminate local water supplies.[14]

In addition to fly ash, ASTM also allows for other pozzolans such as ground glass, silica fume (a by-product of silicon production), or naturally occurring pozzolans. Natural pozzolans, such as those found in volcanic ash, have the potential to significantly reduce the overall emissions associated with cement production. In geographies where natural pozzolans are cost-effective and sustainable to produce, they may serve as a valuable resource in the future if new production of other SCMs (including fly ash and GGBFS) dwindles with the decarbonization of the power and steel sectors.

[viii] See footnote vii on page 17.

[ix] Relevant studies include M. McCarthy, T. Robl, and L. Csetenyi, "Recovery, Processing, and Usage of Wet-Stored Fly Ash," in Coal Combustion Products (CCP's), Elsevier, 2017, 343–367; and I. Diaz-Loya et al., "Extending Supplementary Cementitious Material Resources: Reclaimed and Remediated Fly Ash and Natural Pozzolans," Cement and Concrete Composites, vol. 101 (2019): 44–51.

Related Solutions

1. Know Your Numbers: Performance-oriented specifications

3. Plug and Play: Sensors can save time, money, and materials

State of the Market

Portland limestone cement (PLC) is increasingly used due to the simplicity of implementation by cement producers and the reduction in the emissions intensity of the concrete by 10%. For example, the Colorado Department of Transportation (CDOT) recently used PLC as the basis for the Highway 287 replacement in an effort to meet the state's climate action plan.[15] CDOT's use of PLC also provided a basis for the synergistic inclusion of fly ash into the cement blend for parts of the project, further reducing the embodied carbon content of the concrete.

Although natural pozzolan production is currently small (0.5 Mt/y in 2017),[16] there have been some recent expansions, including Nevada Cement offering a natural pozzolan cement product and Charah Solutions offering a natural pozzolan product through its new grinding facility in California. The Natural Pozzolan Association now lists several producers as well as multiple prospective deposits that could increase the supply across the United States. Alternative waste material pozzolans have also been developed into commercial offerings. For example, Pozzotive's ground glass pozzolan has been used in a number of projects in New York, including pavement for United Nations Plaza and for stations on the 2nd Avenue Subway line.

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Plug and Play

Sensors Can Save Time, Money, and Materials

Using sensors in concrete is a well-established practice that saves resources, but real-time monitoring of temperature and moisture in concrete also facilitates a smaller cement content in mixes, while improving site safety for workers.

Key Takeaways

Affordable, off-the-shelf sensors can assuage safety concerns, save money, and support adoption of low-embodied-carbon concrete.

When compared to laboratory break tests, on-site monitoring speeds construction site activities and provides real-time validation of strength, further adding value to this decarbonization tool.

Instead of using overdesign calculations, which lead to unnecessarily high cement content in mixes, continuous logging of concrete temperature and strength generates precise data, allowing a reduction of cement content that reduces cost and embodied carbon.

Opportunity

Contractors usually measure the strength of concrete by employing cylinder tests, in which a standard amount of concrete is poured on site and monitored to serve as a proxy for concrete used elsewhere on site. In-situ concrete sensors can improve the accuracy of measurement compared with cylinder tests.

Sensors can be used in any kind of concrete, but they take on particular value in the context of low-embodied-carbon mixes. Low-embodied-carbon mixes typically take longer to cure. Contractors on site might be unfamiliar with their use. Sensors allow real-time monitoring, eliminate on-site guesswork, and deliver confidence. SCMs lower the concrete heat of hydration, which can result in a measurement discrepancy between indirect tests using the same concrete blend and testing the strength of the concrete pour directly.[17] The indirect cylinder test can underperform compared to in-place testing since larger pours generate more heat, which affects cure time. Using sensors to measure the early-age strength of concrete provides real-time information superior to cylinder samples, which in turn allows on-site work to proceed quickly and safely, leading to cost savings.

Real-time monitoring of early-age concrete strength allows contractors to proceed with critical operations like formwork removal, post-tensioning, and shore stripping much sooner than if they were relying on laboratory break tests. Maturity meters allow producers to achieve performance goals with greater reliability and speed.

Considerations

Concrete producers must calibrate the mix design in the lab or field before a contractor can utilize the sensor-based maturity method to measure concrete strength. ASTM specifies sensor types suitable for testing relative humidity (important in flooring applications) and strength.[x] The ASTM standard for on-site measurement requires three sensors for the first 1,000 ft^2, and then at least one sensor for every remaining 1,000 ft^2. A 10,000 ft^2 slab of concrete would require 12 sensors, costing less than $1,000 in total.[18]

[x] Specifications are referenced in ACI 228, ASTM F2170, and ASTM C1074.

Related Solutions

1. Know Your Numbers: Performance-oriented specifications

2. Mix It Up: Supplementary cementitious materials (SCMs)

4. Embrace Circularity: Concrete recycling

5. Carbon as a Service: Sequestering CO_2 in concrete

Types of sensors in the Market

Sensors have been used in the industry for 20 years, becoming more accurate and cost-effective over time. There is a wide range of commercially available products, offering a variety of price points and use cases.[19]

Thermocouples: Usually purchased in an adjustable bundle, these units can be connected to a computer to download and analyze the data once the measurements are completed. Wireless devices have been developed as well that upload the thermocouple measurements to the cloud or a smartphone. Although these sensors can be inexpensive, their accuracy is not as precise as other sensors.

Wired temperature and maturity loggers: These loggers address the deficiencies of thermocouples, and their management poses fewer problems on the jobsite as the external unit is not exposed. On the other hand, these have a limited shelf life and cannot be switched off.

Wired sensors with external wireless transmitters: Both thermocouples and loggers present issues, as they need to be connected to external devices. Wireless transmitters, by contrast, are connected to the end of the wires coming out of the concrete to store and transfer the measurements over a wireless network.

Fully embedded wireless sensors: Measurement data is stored on the sensor and can be download from the fully embedded module through various wireless communication protocols such as Bluetooth.

Notable sensor providers[xi]: CommandCenter, ConcreMode by Doka, Concrete Sensors by Hilti, Con-Cure NEX, Converge, Exact Technology, HardTrack by Wake, HOBO, IntelliRock, AOMS Technologies, Maturix by Sensohive, Maturix Smart Concrete Sensors by Kryton, SmartRock by Giatec, and VOrb by Quadrel.

[xi] Mention of sensor brand does not include endorsement.

CONCRETE SOLUTIONS GUIDE

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Embrace Circularity

Concrete Recycling

The simplest way to reduce concrete emissions is to produce less of it—that's where recycling comes in. The rate of change of the built environment often outpaces the longevity of concrete. Although normally treated as a waste material, concrete from decommissioned buildings should be viewed as a resource. When used on-site for nonstructural application (e.g., as base material), recycled concrete offers significant cost savings and obvious emissions reductions.

Key Takeaways

For nonstructural applications, recycled concrete sourced on-site offers approximately 50% cost savings compared with natural aggregate and reduces the volume of new material required.

Among the most promising applications for this material are uses as a base layer for roads, parking lots, and driveways; as backfill material or shoulder stone; and as aggregate in nonstructural concrete.

Current technology for incorporating recycled concrete aggregate in new structural concrete mixes does not achieve significant reductions in embodied carbon.

Opportunity

The Construction Materials Recycling Association estimates that 140 million tons of concrete are recycled annually in the United States,[20] which is approximately 13% of the total natural aggregate produced for construction. Increasing this circularity is a vital step toward a low-carbon future. When approaching a new building project, it is important to recognize old concrete as a new resource.

The application of recycled concrete aggregate (RCA) is best suited to use cases where high strength is not required, such as for base layers in gravel and in pavement concrete. Several studies have demonstrated that the use of recycled concrete aggregate can reduce costs, particularly when the aggregate is processed on-site, eliminating further transport requirements. A direct cost savings for RCA of 60%–80% can be readily achieved when the RCA is used on the same site where it is produced,[21] while reducing life-cycle environmental impacts in emissions and water consumption.[22]

Considerations

Processing RCA is cost-effective compared to using natural aggregate. But when used to replace natural aggregate in concrete for structural applications, the benefits are limited. Unlike natural aggregate, RCA contains adhered mortar, which can result in reduced performance when it is recycled to produce new concrete.[23] Studies also indicate increased contraction as the RCA fraction is increased.[24] As a result, it would be necessary to increase the amount of cement or admixtures used in a mix to offset the strength impacts, cutting into the emissions benefit from the use of RCA.

In order to reduce the variable performance in RCA, further treatment can either remove or fortify the adhered mortar. Several techniques are likely cost-competitive, including mechanical abrasion, heat treatment, and ultrasonic water cleaning for removal, as well as carbonation for fortification.[25] Of these methods, carbonation is particularly promising given its potential to both enhance the RCA properties and reduce carbon emissions by acting as a permanent mineral store of carbon dioxide (see **Solution 5**).

Thus far, these challenges have stymied efforts to achieve significant carbon savings by using RCA in structural applications.[26] Although the carbon emissions reductions for RCA compared with natural aggregate on a mass basis are significant (approximately 66%), the overall impact on embodied carbon becomes nearly negligible due to the increased use of cement, which usually accounts for over 90% of the total associated emissions in concrete.[27] Put simply, the gains are nearly canceled out by losses when RCA is used in mixes with structural applications.

Related Solutions

1. Know Your Numbers: Performance-oriented specifications

2. Mix It Up: Supplementary cementitious materials (SCMs)

5. Carbon as a Service: Sequestering CO_2 in concrete

6. Use Green Heat: Decarbonize kiln technology

Future breakthroughs, such as those discussed in Solution 5, have the potential to change the unfavorable math on using RCA in mixes with structural applications. But until that point comes, RCA remains a highly cost- and carbon-effective material for on-site, nonstructural applications.

State of the Market

In most markets across the United States, companies provide on-site concrete recycling services as well as centralized facilities for processing and upgrading RCA. Several ready-mix companies also offer on-site concrete recycling services.

Promising regulatory changes are also under way. The American Concrete Institute (ACI) committee on concrete with recycled materials is currently updating its guide on removal and reuse of concrete. This guide will provide updated research on RCA use as well as best practices and recommendations for RCA deployment. Meanwhile, public entities are gravitating toward increased uptake of RCA. The City of San Francisco has specified a minimum of 15% RCA in all concrete pavement applications.[28]

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CONCRETE SOLUTIONS GUIDE

Carbon as a Service

Sequestering CO_2 in Concrete

At the cutting edge of concrete innovation is technology that enables concrete to capture and store carbon dioxide. Sequestering CO_2 in concrete traps carbon dioxide through the process of mineralization. Sequestration takes place in one of two ways: either injecting CO_2 into the concrete during the mixing process or curing concrete in a CO_2-rich atmosphere. In both cases, carbon dioxide diffuses into the fresh concrete and transforms the gaseous CO_2 into solid calcium carbonates ($CaCO_3$).[29] This process has the potential to confer co-benefits including improved strength and cure time.

Unlike the other technologies in this guide, carbon sequestration in concrete is not yet mature. Further research and development are necessary to achieve scalable results that maximize positive outcomes for embodied carbon. With additional optimization, this technology has the potential to transform the role of concrete in the global carbon cycle, and it merits attention from stakeholders even at this early stage.

Key Takeaways

Carbon sequestration via CO_2 curing is an immature technology, and applications with consistently positive and verifiable climate benefits have yet to be deployed at scale.[30]

Available data suggests that CO_2 sequestration in mixing cement is more promising than CO_2 sequestration in curing.[31]

The electricity required to deploy CO_2 sequestration via curing is a crucial factor in determining the net impact of these technologies on the embodied carbon content of concrete.[32]

For both mixing and curing, CO_2 injection may offer co-benefits in the form of improved compression strength and cure times.

Opportunity

CO_2 sequestration in concrete has the added benefit of improving concrete performance while reducing embodied carbon. For CO_2 injection during mixing, the main benefit is enhanced compressive strength that allows for improved performance. Additional testing of this application may demonstrate the ability to reduce the cement content of a CO_2-rich mix, further increasing emissions performance. Scaling up this technology may be assisted by the spread of performance-oriented specifications (see **Solution 1**), which could empower concrete producers to create innovative mixes to take advantage of strength gains from CO_2 mineralization.[33]

Aside from mixing, curing concrete in a CO_2-rich atmosphere can be used for precast concrete products, such as roadside barriers and retaining walls, where the curing environment is controllable. In this application, CO_2 replaces steam as a method for increasing the rate of strengthening. Carbonation typically improves compressive strength by 20% in the first 24 hours, compared with unaccelerated curing. CO_2-rich curing also reduces the permeability of the precast concrete, thereby improving its durability (e.g., resistance to sulphate attack).

Considerations

The co-benefits of both of these approaches are complicated by uncertainties about their net impact on the embodied carbon of the final product. The most recent science suggests that, for presently available technologies, carbon injection in curing is likely to lead to a net increase in embodied carbon. Available data suggests carbon injection in mixing can produce a consistent reduction in embodied carbon although strength reductions in some instances can more than offset the benefit.[34]

The uncertainty in this landscape stems from the immaturity of carbon capture technology, direct mineralization processes, and the associated infrastructure required to transport and deliver captured CO_2 to market. The future viability of this technology is closely linked to the market trends in carbon capture and storage, and to future process innovations in how captured CO_2 is deployed in the concrete sector.

There are limits to the amount of CO_2 that can be sequestered in concrete. Concrete's strength is derived from the reaction of calcium silicates with water. As a result, only a small portion of the silicates are available for reaction with CO_2. Currently, the amount of CO_2 sequestered is also limited by the cost of delivering CO_2 to a construction site.

One of the greatest challenges in this technology revolves around CO_2 use. A recent review accounting for the upstream emissions of CO_2 used in concrete found that in many cases, the emissions (and energy use) from utilizing the CO_2 can offset any sequestration benefit, ultimately causing more climate harm than good.[35] This review also highlighted the uncertainties of how this process affects strength during curing, potentially requiring the use of additional portland cement to maintain integrity, which eliminates any gains from directly sequestered CO_2.

These findings are not unexpected, given that CO_2 can consume some of the active strengthening component (calcium silicate) in cement, and the research highlights the need for precise dosing during curing and mixing. However, if the correct dosing of CO_2 can consistently result in a strength benefit, it may be possible to reduce the cement content of a given concrete mixture, thereby lowering embodied carbon. Further research on the optimal CO_2 curing protocol will be needed to determine whether strength gains can be consistently achieved. Looking ahead, future opportunities could include synergistic applications of CO_2 mineralization during curing and mixing of cement blended with SCMs (see **Solution 2**), or using carbonation to improve the performance of RCAs (see **Solution 4**).

Although key questions remain about the future of this technology, the technology continues to show promise. Early-stage technologies, such as carbonation of recycled concrete aggregate, CO_2 sequestration of alternative magnesium-based binders, CO_2 dissolution in concrete mixing water, and CO_2 mineralization of aggregates, are currently being developed and have the potential to unlock significant decreases in embodied carbon.

Related Solutions

1. Know Your Numbers: Performance-oriented specifications

2. Mix It Up: Supplementary cementitious materials (SCMs)

4. Embrace Circularity: Concrete Recycling

State of the Market

Although several companies have developed carbon sequestration techniques over the years, only a few have reached commercialization.[36] Blue Planet, Carbon Engineering, CarbonCure, Solidia, and Svante are currently providing leading carbon capture, utilization, and storage (CCUS) technologies in the built environment, each with different roles.

Company	Technology Type	Description
CarbonCure	CO_2 injection during mixing for ready-mix concrete applications	CarbonCure sells a technology that injects carbon dioxide captured from industrial processes into portland cement along with water. This is completed without major implementation barriers, as a "Valve Box" connects to a CO_2 tank stored on-site and injects a precise quantity of CO_2 into the concrete during the mixing phase. With around 300 producers using its technology already, the company has an ambitious expansion plan to reach a 500 Mt CO_2 reduction goal.
Solidia	CO_2 curing of precast concrete products	Solidia's technology involves mixing a cement powder with sand and then filling in open spaces with water and carbon dioxide. Founded in 2008, Solidia received the support of cement majors like LafargeHolcim and of the US Department of Transportation's Federal Highway Administration. Lafarge and Solidia developed a reduced CO_2 cement that, together with a proprietary concrete mix design and a specialized curing process utilizing CO_2, purportedly creates concrete with up to a 70% lower carbon footprint than traditional portland cement systems.
Blue Planet	CO_2 mineralization of aggregate prior to concrete mixing	Blue Planet uses CO_2 as a raw material for making carbonate rocks that can be used in place of natural limestone rock. The company is in the process of building a plant in Pittsburgh, California, and recently completed a successful test project at San Francisco International Airport.
Carbon Engineering	CO_2 capture and supply	Carbon Engineering uses a direct air capture (DAC) technology that can capture CO_2 directly from the atmosphere and supply it to multiple sectors that use CO_2.
Svante	CO_2 capture and supply	Svante, like Carbon Engineering, uses a carbon capture technology that enables circularity and reduction within supply chains by capturing CO_2 directly from the cement kiln.

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CONCRETE SOLUTIONS GUIDE

Use Green Heat

Decarbonize Kiln Technology

Cement kilns are the site of 90% of the emissions associated with concrete production. Although 50% of these emissions are produced directly from the calcination of limestone,[37] and can therefore only be eliminated through the use of SCMs or carbon capture and storage, the remaining 50% of emissions can be mitigated through interventions at the kiln itself.

Key Takeaways

Cement kilns are responsible for 90% of emissions in concrete produced with portland cement.

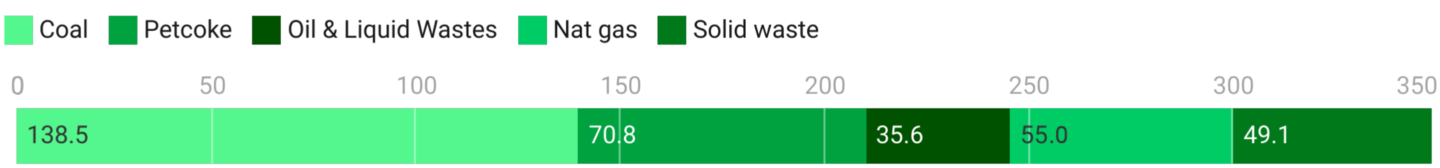
Despite the long life of kilns and challenges of deep retrofits, reducing the emissions from process heat can be accomplished with fuel switching and efficiency upgrades.

These low-risk, high-yield opportunities have the potential to deliver 18% emissions reductions without requiring deep retrofits.[38]

Opportunity

More than 90% of the readily mitigable emissions at kilns come from burning fossil fuels to reach the high temperatures required to drive the clinker sintering reactions. In the past several decades, US kilns have already made terrific gains in energy efficiency, logging a 53% reduction in the energy intensity of kilns between 1970 and 2017, due in part to the shift away from wet kilns. However, these emissions remain high, and there are ample opportunities for further reducing these emissions through efficiency improvements (as demonstrated by the EPA's ENERGY STAR program[39]) and switching to biomass or other low-carbon fuels. Many of these improvements will also deliver cost savings for cement producers.

Exhibit 6: Energy consumption in US cement kilns by fuel type (PJ/y)



Fuel usage in cement kilns is dominated by fossil sources. There are opportunities to utilize sustainably produced biomass-based fuels to reduce emissions.

Considerations

Data from the US Geological Survey on the fuel mix used by cement kilns indicates that approximately 60% of heat comes from coal-based fuels, with the remainder from natural gas and wastes.[40] Although waste fuels can be cost effective and provide certain environmental benefits (e.g., avoiding the landfill), these fuels can also cause localized issues, such as airborne particulate matter.

One near-term opportunity for cement kilns to reduce the emissions associated with heat generation is to switch to sustainably produced biomass-based fuels. Life-cycle emissions impacts of different types of biomass should be taken into account and factored into the decision-making process. Widespread adoption would require some expansion in biomass fuel availability, but the additional demand associated with switching all US cement production to biomass fuels (~350 PJ) is

equivalent to just 7% of the total biomass energy produced in the United States in 2019 (~5,300 PJ). There are further barriers to biomass uptake besides supply and distribution, including lack of clarity from regulators on permitted fuels, lengthy permitting timeframes for new fuels, and preference for certain fuels among local communities.

The switch to biomass would likely increase fuel costs compared with the current mix. Energy efficiency improvements could help to limit this impact by reducing the required amount of biomass fuel required. Based on biomass price ranges from IRENA,[41] wood wastes, agricultural residues, and landfill gas could be cheaper than coal in some instances and would be less expensive than natural gas in almost all cases. For example, coal costs to produce a ton of cement are US$5.85, whereas the lowest-cost wood waste (US$0.50/GJ) would only cost about US$2.00 per ton of cement. However, the supply of these alternative fuel sources is limited. Costs also vary significantly based on the proximity of the cement producer to a suitable biomass feed source. While these issues add a degree of friction to fuel transition at kilns, they are well-defined problems with straightforward solutions.

Oxygen enrichment can also reduce fuel demand by 3%–5% by limiting the amount of nitrogen that is heated in the kiln. This effectively allows for some electrification of the kiln energy requirement, as direct fuel consumption is replaced with electrical energy for oxygen production. The total amount of abatement from this strategy is dependent on the emissions intensity of the electricity source. Oxygen enrichment may also assist in positioning a kiln for carbon capture and storage (CCS) in the future, as it will increase the carbon dioxide concentration in the off-gas.

Additional fuel options may be available in the future, depending on the success of ongoing research and development. These include the possibility of using green hydrogen or direct electrification of high-temperature processes (e.g., using a plasma torch).

Lastly, electricity consumption at cement kilns (primarily associated with grinding of clinker) can be further reduced to achieve improved efficiency. For example, replacing ball mills with vertical roller mills can reduce grinding energy by 25 kWh/ton while providing operating cost savings of 30%–40%. Recovery of waste heat for cogeneration (or on-site renewable generation) of electricity would also assist in reducing the external electricity demand and associated emissions. In some markets, the existing regulatory regime presents a barrier to implementing this strategy, as concrete producers are subject to fixed charges from utilities.

Related Solutions

2. Mix It Up: Supplementary cementitious materials (SCMs)

State of the Market

The ENERGY STAR program has an industry benchmarking system for both cement and concrete production facilities. These systems offer a detailed guide for energy efficiency improvements and cost-saving opportunities in cement making, which can be found in our additional resources at the end of this guide. The benchmarking program allows facilities that receive a rating of at least 75 out of 100 to carry the ENERGY STAR label, which developers and concrete producers can look for when procuring cement.

Despite the resources available and the cost-effectiveness of efficiency upgrades, there is still substantial room for improvement. A 2013 ENERGY STAR guide for the cement industry reported that the highest-efficiency kilns use 2.9 GJ/ton, which is 27% less than the current average. These reductions are primarily achieved by the recycling of heat through the incorporation of multistage pre-heaters and pre-calciners. Exhibit 6 indicates the cost and carbon savings still left on the table.

CONCRETE SOLUTIONS GUIDE

Conclusion and Resources

Conclusion

Although concrete is frequently referred to as a "harder-to-abate" sector of the economy, opportunities abound for decarbonizing this industry using proven and scalable technologies. As producers, developers, and policymakers begin to mainstream these improved processes, they should also maintain an awareness of the rapidly developing innovations in this space, which promise to deliver further reductions in embodied carbon in the years to come.

Resources

The solutions within this guide are a limited selection of actionable and cost-effective approaches to reducing embodied carbon in concrete. RMI continues to advance knowledge and practice of low-embodied-carbon building design, policy, and procurement. For resources related to RMI's work in embodied carbon, please visit:
https://rmi.org/insight/reducing-embodied-carbon-in-buildings

The following resources can help concrete purchasers and producers implement the opportunities highlighted in this guide:

Tools:

- *Guide to Improving Specifications for Ready Mixed Concrete* (**https://www.nrmca.org/wp-content/uploads/2020/10/GuideToSpecs.pdf**)
- Embodied Carbon in Construction Calculator (EC3) (**https://buildingtransparency.org/ec3**)
- SM Transparency Catalog (**http://www.sustainableminds.com/**)
- ZGF's Concrete LCA Calculator (**https://www.zgf.com/news_post/lca-calculator-reduces-concretes-embodied-carbon/**)

Reports:

- RMI's ***Reducing Embodied Carbon in Buildings*** (**https://rmi.org/insight/reducing-embodied-carbon-in-buildings**)
- Breakthrough Energy Manufacturing Policy Playbook: Manufacturing (**https://www.breakthroughenergy.org/us-policy-overview/manufacturing**)

Embodied Carbon and LCA Research/Resources:

- CLF 2021 Material Baselines (**https://carbonleadershipforum.org/material-baselines/**)
- Carbon Smart Materials Palette (**https://materialspalette.org/concrete/**)

Templates:

- EPD Request Letter Template (**https://www.buildingtransparency.org/resources/ec3-downloads/**)
- Model Specifications (**https://carbonleadershipforum.org/model-lca-specifications/**)

Voluntary Embodied Carbon Commitments:

- Engineers: SE2050 Commitment to Net-Zero (**https://se2050.org/**)
- Architects: 2030 Challenge for Embodied Carbon (**https://architecture2030.org/2030_challenges/embodied/**)
- Cities: C40 Clean Construction Declaration (**https://www.c40.org/clean-construction-declaration**)

Compilation of Embodied Carbon Policy in the United States:

- CLF policy map (**https://carbonleadershipforum.org/clf-policy-toolkit/#map**)

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