Achieving Net Zero Concrete in California

Pathways, Opportunities, & Barriers

July 2023

CAL CIMA
California Construction And Industrial Materials Association

About CALCIMA

The California Construction & Industrial Materials Association (CalCIMA) is a trade association for the construction and industrial material industries in California, which includes aggregate, industrial mineral, ready mixed concrete, and asphalt producers. In all, there are about 70 producer member companies that include over 250 production sites in every county of California. Our members also include over 70 supplier and service providers to the industry. CalCIMA members represent the vast majority of concrete manufactured in the state.

California Construction And
Industrial Materials Association

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Acronyms

ASTM = American Society for Testing and Materials

Caltrans = California Department of Transportation

CCUS = Carbon Capture, Utilization, and Storage

CNG = Compressed Natural Gas

EPD = Environmental Product Declaration

GGBS = Ground Granulated Blast Furnace Slag

GHGs = Greenhouse Gases

LCFS = Low Carbon Fuel Standard

PLC = Portland Limestone Cement

RD&D = Research, Development, and Deployment

RNG = Renewable Natural Gas

SCM = Supplementary Cementitious Material

Executive Summary

The California concrete industry is committed to reducing its GHG emissions footprint and reaching net carbon neutrality by 2045. This roadmap outlines the options for reaching “net zero concrete” without undue delay. Although focused on the California concrete industry, the roadmap incorporates and is aligned with similar efforts from other state, national, and international organizations that represent stakeholders throughout the entire cement-concrete-construction value chain. The goal of achieving carbon neutrality is a natural continuation of the industry’s longstanding efforts to consistently improve environmental performance and infrastructure resiliency.

Concrete is essential to the functioning and development of modern society. As a result, it is the second most consumed material on earth after water and the most widely used building material. Although the terms “cement” and “concrete” are used interchangeably by the public, they refer to unique manufacturing processes and uses. Specifically, “cement” is the glue that, when activated with water, holds together the constituent ingredients in "concrete" — a pourable mix of cement, aggregates (typically sand and crushed rock), water, and admixtures that hardens into a rock-like material. Compared to other building materials, concrete offers a wide range of advantages, including superior strength and durability, enhanced disaster resilience, and long-term ecoefficiency, and opportunities to increase recycling and circularity.

In environmental terms, distance matters; using locally produced and delivered concrete reduces associated transportation emissions. In California, concrete is produced by hundreds of ready-mix batch plants and other operations that support and serve local communities in every corner of the state. With such a large and diverse industry, there is no centralized, top-down point of control from which to effectively regulate the industry or “one-size-fits-all” solution that is feasible for all companies. Given this reality, the California concrete industry recognizes that its best role is as an advocate, facilitator, and accelerator of broader value chain decarbonization efforts.

Concrete manufacturing consists of two primary steps: measuring raw materials (batching) and combining all the ingredients to produce concrete with uniform color, consistency, and performance (mixing). In most cases, these two steps are conducted at concrete batch plants, although mixing may also be performed enroute to or at the job site. Once placed, concrete enters the “use phase” – where it offers significant GHG efficiency advantages compared to the use phases of other building materials. Once a concrete structure has outlived its economic life, it is demolished and enters the “end-of-life phase.”

GHG emissions associated with cement manufacturing comprise the majority of embodied emissions in a unit of concrete (nearly 90%). The remainder of the embodied emissions in a unit of concrete stem from batching, transportation, raw materials extraction and processing, and other situation-dependent emissions. Furthermore, concrete captures and safely sequesters CO_2 from ambient air (“recarbonation”) over the life of a structure, meaning that concrete is also a carbon sink. As a result, achieving net zero concrete does not necessarily equal eliminating all GHG emissions from the production process.

Charting a path to carbon neutrality in the California concrete industry requires a flexible approach that recognizes the unique challenges facing communities and the industry, including prescriptive specifications, limited control over the GHG footprint of raw materials, existing regulations and regulatory programs, and a limited supply and availability of alternative raw materials. Accordingly, this roadmap outlines a wide range of opportunities to reduce the GHG emissions associated with concrete used in the state, as summarized in the table below.

Given the diverse size and structure of companies that make up the California concrete industry, there is no “one right path” to achieving net zero concrete. Rather, the best approach is for policymakers to unlock barriers across the full range of pathways — providing each concrete producer with the flexibility and choices needed to chart a path to decarbonization that aligns with their resources, constraints, and circumstances. It will also require active cooperation between the concrete industry and a variety of stakeholders throughout the cement-concrete-construction value chain, including but not limited to architects, engineers, developers, owners, construction contractors, and material suppliers. As the industry that sits at the nexus of this value chain, the California concrete industry is committed to doing its part to make net zero concrete a reality.

Summary of Key Pathways, Likely Timing, & Relative Impact on GHG Emissions

	Timing	Impact
Pathway 1: Implement Performance-Based Specifications		
Pathway 2: Use Less GHG-Intense Raw Materials		
Lever 2.A: Expand the Use of Lower Carbon Cements	Mid-Term	High
Lever 2.B: Expand the Use of Supplementary Cementitious Materials	Near-Term	High
Pathway 3: Optimize Design, Decrease Waste, & Increase Circularity		
Lever 3.A: Optimize Concrete Use	Mid-Term	Medium
Lever 3.B: Increase Concrete Circularity	Mid-Term	Medium
Pathway 4: Increase the GHG Efficiency of Concrete Operations		
Lever 4.A: Automate Concrete Manufacturing Operations	Near-term	Low
Lever 4.B: Decrease GHG Emissions from Concrete-Related Transportation	Near-term	Low
Pathway 5: Increase the Recarbonation Potential of Concrete		

Section 1

Roadmap Introduction

The global community has converged around the goal of "net carbon neutrality" — that is, ensuring that the amount of greenhouse gases (GHGs) generated by society is at least equal to the amount stored through sinks. According to recent scientific assessments, society must achieve carbon neutrality by midcentury to avoid the worst impacts of climate change.[1] Consistent with that target, California has committed to achieving statewide carbon neutrality by 2045 and is actively pursuing a range of options to rapidly shrink its footprint over the next two decades.

The California concrete industry recognizes the importance of reaching global carbon neutrality as quickly as possible.[2] We support the state's climate policy goals and look forward to collaborating with policymakers, regulators, and other stakeholders to achieve them. We are also committed to reducing the industry's GHG emissions over time with the ultimate goal of achieving "net zero concrete" in California by 2045.

With those goals in mind, this roadmap offers a framework for thinking about how to make net zero concrete in California a reality. It centers around the fact that the concrete industry operates within the cement-concrete-construction value chain — a complex ecosystem that includes but is not limited to aggregate producers, cement manufacturers, concrete producers and manufacturers, suppliers of cement substitutes and admixtures, construction contractors, engineers, architects, agencies, developers, and project owners across the private and public sectors. On the one hand, the concrete industry sits at the nexus of this value chain and, therefore, has an important role to play in reducing its GHG emissions. On the other hand, the concrete industry is just one of many important actors within this extensive value chain and, therefore, has a limited ability to unilaterally drive progress.

This roadmap draws from similar efforts from other state, national, and international organizations that operate within the cement-concrete-construction value chain. That includes but is not limited to the National Ready Mixed Concrete Association (NRMCA), the American Concrete Institute, the California-Nevada Cement Association, the Portland Cement Association, and the Global Cement and Concrete Association. This roadmap draws from prior literature while also acknowledging that the California concrete industry is one-of-a-kind due to its unique combination of market size, geographic diversity, competitive environment, regulatory constraints, and proximity to key raw materials, among other factors.

Finally, this roadmap builds on the California concrete industry's long-standing efforts to significantly improve its environmental performance and advance the state's environmental goals. It does not represent a new focus on environmental issues for the industry — rather, this roadmap represents a deepened commitment to advancing the state's environmental goals while ensuring that the industry remains viable, vibrant, and capable of contributing to California's economic, infrastructure, resiliency, and affordable housing goals.

The California concrete industry is committed to using its position at the nexus of the cement-concrete-construction value chain to advance the state's policy ambitions — but we cannot do it alone. The value chain is too vast and too complex to transform without a "whole value chain" approach that is supported by a common set of goals, clear-eyed public policies, and close coordination and collaboration across all stakeholders. Simply put, achieving net zero concrete by 2045 will require a team effort, and the concrete industry is prepared to play a leading part in making net zero a reality.

Section 2

Primer on Concrete & The California Concrete Industry

Concrete is an indispensable construction material that modern economies rely on to build homes, offices, roads, bridges, schools, and other critical infrastructure like levees and dams. Concrete is the second most consumed material on earth after water and the most widely used and resilient building material.

Despite the necessary, ubiquitous, and everyday role that concrete plays in our lives, there are common misunderstandings about the product, its manufacturing process, and the widespread benefits that it provides societies. For instance:

- Many people use the terms “cement” and “concrete” interchangeably, despite the fact that they are distinct products with very different manufacturing processes and uses.
- Many people assume that manufacturing concrete is a GHG-intensive process, despite the fact that the vast majority of the product’s GHG footprint is associated with the production of cement.
- Many people believe that concrete is much more GHG-intensive than other construction materials, despite the fact that the GHG emissions associated with concrete are typically lower than other materials when measured on a lifecycle basis.

These misunderstandings and misperceptions tend to complicate policy discussions about how to most effectively decrease GHG emissions. We encourage all stakeholders to invest time in understanding the nature and origin of GHG emissions throughout the cement-concrete-construction value chain.

What is concrete?

Concrete is comprised of five main ingredients:

1. **Cement:** The water-activated “glue” that binds together the other raw materials in concrete to form a hard, rock-like material when installed.
2. **Supplementary Cementitious Materials (SCMs):** Additional raw materials with cementitious properties added to some concrete mixes in lieu of cement to alter the mix’s properties (e.g., strength, appearance, and GHG footprint), including but not limited to fly ash, slag, natural pozzolans, and calcined clay.
3. **Aggregates:** A mix of fine aggregates (typically sand) and coarse aggregates (typically alluvial rock or crushed stone) that makes up the bulk of a unit of concrete.
4. **Water:** Activates the binding properties of cement to form a hardened mixture of cement and aggregates.
5. **Admixtures:** Materials added to a mix to improve or alter its properties (curing time, workability, etc.).

The specific mix of raw materials varies from producer to producer and based on use — often at the discretion of entities further down the value chain, like engineers and architects. Exact mixes can also vary depending on the local availability of raw materials, building codes, and other regulatory requirements.

What are the primary attributes and benefits of using concrete?

Concrete has a wide range of critical attributes. These attributes result in a suite of family and community benefits that explain why concrete is the second most utilized product after water. They include but are not limited to:

Availability & Affordability: The local availability of raw materials, such as limestone for cement and aggregates and water for the concrete mix, allows for the efficient production of concrete. Concrete has propelled millennia of economic development due to its affordability and worldwide availability.

Strength & Durability: Built to withstand the rigors of modern civilization, concrete is the building material of choice for the world’s critical infrastructure and architectural marvels. The exceptional strength and longevity of concrete make it a preferred construction material.

Versatility: From sidewalks to complex bridges, concrete can be formed into any shape or strength — and can even be placed underwater. Concrete's exceptional versatility allows it to meet the challenge of any application, use, or form.

Disaster Resistance & Resilience: Concrete provides California's communities with maximum protection from fires and floods compared to other building materials. In fact, since concrete walls, floors, or ceilings do not rot or burn, communities and businesses can recover from natural disaster and can do so more quickly and affordably.[3]

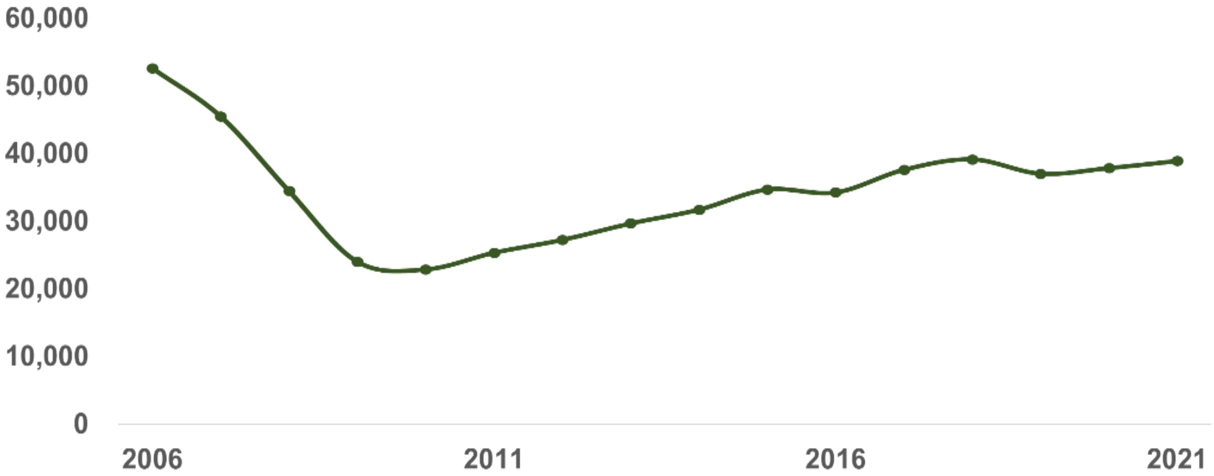
Long-Term Eco-Efficiency: Concrete, compared to alternatives like wood and steel, provides substantial energy savings during the use phase of a structure. When energy savings over the full lifespan of a concrete building are incorporated into GHG accounting, concrete construction is often more eco-efficient and easier to reuse than other building materials.[4]

Who Makes Up the California Cement Industry

The California concrete industry consists of hundreds of ready-mix batch plants and other operations that support and serve local communities in every corner of the state. It is an important source of economic growth and well-paying jobs within the state. For instance, as of 2020, the California ready-mix industry employed more than 7,600 workers at an average wage of more than $72,000 per year.[5]

The concrete industry is very diverse with respect to size, ownership type, and degree of vertical integration. As of 2020, the California ready-mix industry consisted of more than 350 establishments.[6] These establishments range from large, complex operations that are located around major sources of demand to small, family-run "mom-and-pop" operations, many of which serve more rural areas of the state. Some operate as subsidiaries of multinational companies and many others (both large and small) operate as independently owned businesses. Some operate as part of a vertically integrated company (e.g., the parent and/or affiliated company may make aggregates and cement or operate a construction division), while others focus exclusively on manufacturing, selling, and delivering concrete.

Figure 1. California Ready-Mix Concrete Production, 2006-2021



National Ready Mix Concrete Association (2022). Ready Mixed Concrete Production Statistics, 1998 – 2021, California (link)

What are the policy implications of the California concrete industry's structure?

The concrete industry's size, diversity, and position within the supply chain have several important policy implications. First, regulating concrete manufacturers is likely an inefficient lever to reduce full concrete value chain emissions, as it would require a new policy regime to regulate hundreds of entities of varying size and complexity. Second, the concrete industry is ill-suited to a one-size-fits-all approach to regulation that assumes that all ready-mix operators are similarly sized, located, equipped, or positioned to comply in a successful and sustainable fashion. Third, the industry cannot unilaterally drive down the GHG footprint of concrete given that: (1) the vast majority of GHG emissions are generated upstream and (2) the demand for lower carbon concrete is primarily dictated by downstream actors, such as architects, engineers, contractors, developers, and project owners.

In sum, although there are select opportunities for it to reduce its direct GHG emissions, the California concrete industry's most valuable role in advancing the state's climate goals is likely to be collaborating and coordinating with stakeholders throughout the value chain to support changes in how cement is made and how concrete is designed, specified, ordered, delivered, reused, and recycled.

Progress So Far: The California Concrete Industry's Contributions to Environmental Improvement

The California ready-mix industry continues to implement a wide range of measures to reduce the environmental footprint of concrete, including but not limited to:

- **Increasing the use of cement substitutes**: California concrete producers have contributed to significant reductions in GHG emissions by partially replacing cement with substitutes, including higher proportions of inter-ground limestone (i.e., Portland limestone cement) and commonly used SCMs (e.g., fly ash and slag).
- **Expanding the reuse and recycling of concrete materials:** California concrete producers urged Caltrans to adopt the first-in-the-nation specification to allow for the use of up to 15% returned fresh concrete in concrete mixes.[7]
- **Converting fleet vehicles to lower carbon fuels:** California concrete producers have been converting their diesel fleets to alternative near-zero emission fleets by using fuels such as renewable natural gas and renewable diesel.
- **Increasing the use of recycled water in concrete mixes**: California concrete producers have been leaders in using recycled water in their concrete mixes.[8]

Section 3

Understanding the Concrete Lifecycle

Concrete manufacturing consists of two main steps: (1) measuring ingredients prior to mixing (i.e., batching) and (2) combining all the ingredients together to ensure uniform color, consistency, and performance (i.e., mixing).

Most concrete production occurs at a batch plant, which is a facility to batch and load ready-mix trucks (“mixers”) with the correct mix of ingredients. Batch plants procure the key ingredients of concrete: cement, coarse aggregates (e.g., gravel), fine aggregates (e.g., sand), water, and other admixtures or SCMs.

A batch plant then receives orders from customers and mixes these ingredients together to create concrete that meets the specifications of a particular job. Mixing can be done at the batch plant, during transit, or at a portable plant on the project site. Once concrete is installed at the project site, excess product may be returned to the batch plant for reuse, recycling, and/or disposal.

GHG emissions associated with the raw materials, production, transportation, and placement of concrete is generally referred to as concrete’s “embodied” emissions, although the exact scope could be different depending on the focus of a particular analysis.

Concrete then enters the “use phase” of the lifecycle as it serves its function as part of a building, highway, bridge, or other structure. GHG emissions associated with the use phase of concrete are often far lower than those associated with the use phase of alternative construction materials over the lifetime of the structure.

Finally, the concrete enters the “end-of-life phase” of the lifecycle, when it is demolished and then recycled (e.g., used as coarse aggregates for new concrete), downcycled (e.g., crushed and used as road base), or disposed of in landfills. Concrete is unique among other building materials in that, once demolished, a significant share of the material can be reused for subsequent projects. Furthermore, over the course of the entire lifecycle, concrete absorbs atmospheric CO_2 through a naturally occurring process known as “recarbonation.”

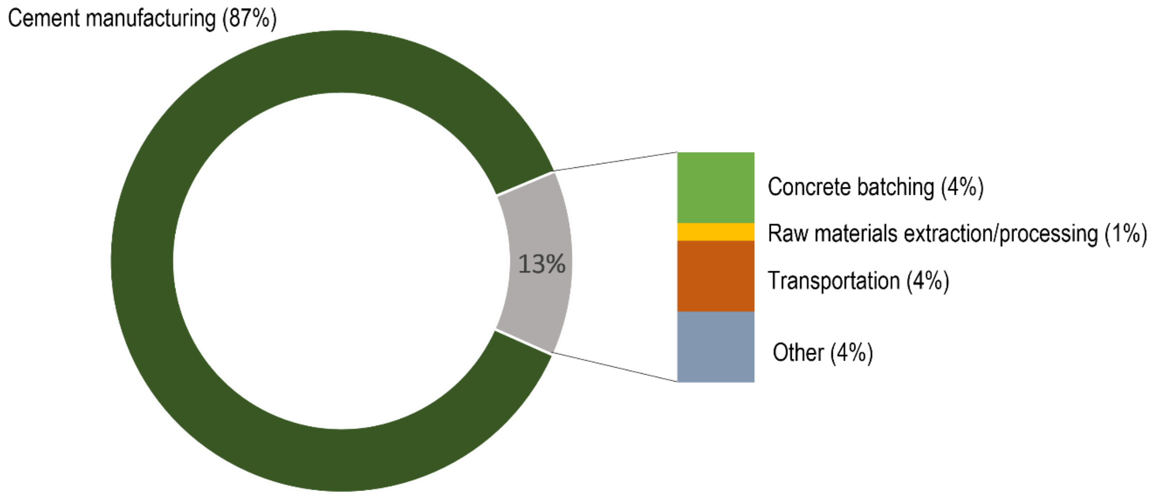
About Concrete Recarbonation

Concrete is unique among other manufactured building materials as it is also a sink of GHG emissions. Hydrated cement in concrete reacts with the ambient environment which, over time, gradually absorbs atmospheric CO_2 and sequesters it in the concrete.[9] In its 2018 assessment report, the United Nations Intergovernmental Panel on Climate Change recognized the recarbonation effect and for the first time incorporated it into the global emissions inventory.[10] Although the exact amount of GHG savings associated with recarbonation heavily depends on the assumed circumstances (the type of demolition, end-of-life handling, waste storage, etc.), estimates tend to range from a low of roughly 5% of the CO_2 associated with manufacturing concrete to a high of 25-30%. Regardless, recarbonation is a significant piece of the puzzle and should be accounted for when measuring and evaluating concrete’s overall impact on GHG emissions.

Section 4
Primary Sources of Embodied GHG Emissions in Concrete

The first step in developing a framework for reducing the GHG emissions associated with concrete is understanding the scope, scale, and nature of those emissions. For the purposes of this report, we focus on “embodied emissions” — that is, the GHG emissions associated with every step of the process in the value chain up until concrete is delivered to the job site.[11] Within that scope, there are five primary sources of GHG emissions that contribute to the overall embodied emissions footprint associated with concrete.

Figure 2. Sources of Concrete Embodied Emissions



Concrete Embodied Carbon Footprint Calculator. (2023) Circular Ecology. (link)

1. Cement Manufacturing (~87%)

Cement is the essential ingredient in concrete, as it binds the other constitute materials together. It also represents the vast majority of the embodied GHG emissions associated with concrete.

2. Concrete Batching (~4%)

Concrete batch plant operations represent a small fraction of the GHG emissions associated with producing concrete products. These activities include batching, mixing, and materials handling. GHG emissions generated at the concrete batch plant level can be mitigated through electrification and energy efficiency improvement.

3. Transportation (~4%)

Concrete manufacturing entails transporting raw materials (particularly cement and aggregates) to the concrete batch plant, as well as transporting ready-mix concrete from the batch plant to job sites. Mitigation of GHG emissions associated with these activities can be achieved through the decarbonization of heavy-duty transportation vehicles via electrification and/or the use of low-carbon transportation fuels (e.g., renewable natural gas).

4. Raw Materials Extraction/Processing (~1%)

The manufacturing of concrete also entails mining the raw materials used in cement and concrete manufacturing, including but not limited to limestone, aggregates, gypsum, and clay. These activities typically constitute a very small fraction of the overall GHG footprint associated with concrete.

5. Other (~4%)

Other embodied emissions include, on occasion, producing and processing fossil fuels that are used for cement manufacturing and transportation. Embodied emissions that fall under this category are outside the sphere of influence of the concrete industry and — accordingly — this report does not prescribe a pathway to decarbonization for this category. Functionally, as a result of California's broader net zero carbon emissions goals, emissions falling under this category will be eliminated by 2045.

Implications

The uneven nature of concrete's embodied emissions profile reinforces three critical points. First, given that the vast majority of concrete's GHG footprint is due to the emissions associated with cement manufacturing, achieving net zero concrete in California will primarily hinge on the success of efforts to decarbonize cement manufacturing. Second, given that only a small share of the GHG emissions associated with concrete are within the concrete industry's direct control, regulators should take extra care to ensure that any direct GHG emission reduction requirements applied to the concrete industry are scoped exclusively to processes and decisions within the concrete industry's direct control. Finally, given that some emissions are associated with transportation and mineral extraction, regulators should take extra care to ensure that any direct GHG emission reduction measures applied to the concrete industry are not overlapping with or duplicative of existing or planned regulations that address these same sources of emissions.

Section 5
Achieving Net Zero Concrete in California

With respect to the California concrete industry, the importance and challenge of decarbonization is framed by a handful of basic facts:

- **Concrete demand is increasing:** California's demand for concrete has increased significantly over the past decade. For instance, California concrete production, which is a good proxy for demand given that concrete is not imported or exported, increased by more than 40% from 2012 to 2021.[12] Future demand is likely to remain strong in light of the state's infrastructure and development goals.
- **Customers create concrete specifications:** The bulk of concrete in California is manufactured or batched to meet specifications provided by customers (private developers, government agencies, etc.), which limits the industry's discretion to meet performance needs while also adjusting and optimizing concrete mixes to minimize GHG emissions.
- **Cement drives GHG impacts:** The vast majority of the GHG emissions embedded in concrete are associated with the manufacturing of cement and as a result, efforts to decarbonize the cement industry will have a substantial impact on the state's ability to achieve net zero concrete.
- **Other drivers of GHG impacts are regulated:** The balance of GHG emissions that are generated in the concrete industry are associated with electricity use, transportation fuels, and other activities that are already highly regulated by at least one state climate program.

The following section outlines a wide range of options that can reduce the GHG emissions associated with concrete. This roadmap is not intended to be a step-by-step plan to get to net zero, but rather a framework for understanding the opportunities associated with various pathways and the barriers that must be overcome to capitalize on them.

Table 1. Key Pathways, Likely Timing, & Relative Impact on GHG Emissions

	Timing	Impact
Pathway 1: Implement Performance-Based Specifications		
Pathway 2: Use Less GHG-Intense Raw Materials		
Lever 2.A: Expand the Use of Lower Carbon Cements	Mid-Term	High
Lever 2.B: Expand the Use of Supplementary Cementitious Materials	Near-Term	High
Pathway 3: Optimize Design, Decrease Waste, & Increase Circularity		
Lever 3.A: Optimize Concrete Use	Mid-Term	Medium
Lever 3.B: Increase Concrete Circularity	Mid-Term	Medium
Pathway 4: Increase the GHG Efficiency of Concrete Operations		
Lever 4.A: Automate Concrete Manufacturing Operations	Near-term	Low
Lever 4.B: Decrease GHG Emissions from Concrete-Related Transportation	Near-term	Low
Pathway 5: Increase the Recarbonation Potential of Concrete		

Innovating to Net Zero:
Driving Deep Decarbonization with Research, Development, & Deployment

Growing investment in decarbonization by companies, governments, and agencies has resulted in increased concrete industry research and development (R&D) activity. However, most of the emerging technologies in this space that are at or near market readiness are not yet available at the cost or scale needed to rapidly decarbonize the cement-concrete-construction value chain in line with the 2045 carbon neutrality target. That said, with increased investment and a favorable policy environment, accelerating the pace of research, development, and deployment (RD&D) of breakthrough technologies could potentially drive large reductions in the net carbon footprint of California concrete in the longer term.

There is a wide range of emerging technologies that have the potential to eventually contribute to achieving net zero concrete, including but not limited to:

- **Carbon Negative Aggregates:** Active RD&D is underway to develop carbon negative aggregates that, when used in place of traditional aggregates, can reduce the net carbon footprint of concrete.
- **Bioengineering:** There are multiple active R&D streams seeking to produce carbon neutral (or negative) raw materials using bioengineering of various natural processes.
- **Alkali-activated Binders:** Using alternative binders (instead of portland cement) that can be activated by alkaline substances (rather than water) can offer GHG reductions and additional water savings.
- **Sequestering CO_2 in Concrete:** Carbon can be directly stored in concrete structures using either gaseous or mineralized CO_2. If proven out and deployed at scale, such technologies could enable the concrete industry to serve as a significant “carbon sink” that securely stores CO_2 from other sources.

Challenges

Most of the companies pursuing these technologies are in the pilot or demonstration stage of deployment and have not reached a sufficient scale to decarbonize California’s concrete outside of individual projects or niche applications. While some of these technologies may be market ready and at commercial scale in the next two decades, it is highly uncertain whether any of them will reach the market penetration needed to substantially reduce the concrete industry’s GHG footprint by 2045.

Current RD&D policy, investment, and market conditions are not fully aligned with the urgency of meeting the goal of achieving net zero concrete by 2045. Without a substantial change in these conditions, scaling up technological decarbonization solutions in the concrete industry is constrained by limited availability, high costs, minimal customer demand, and the risk averse culture of construction industry stakeholders.

Pathway 1

Implement Performance-Based Specifications

The Opportunity

Current concrete specification practices and standards are incompatible with GHG mitigation efforts. Customers typically order concrete based on specifications that dictate fixed amounts and ratios of raw ingredients. For example, even if a concrete batch plant can provide a concrete mix for a Caltrans project that fulfills performance requirements with significant GHG savings relative to regular concrete, it cannot supply the lower carbon concrete mix unless it convinces Caltrans to explicitly change its specifications.

This highly prescriptive approach to ordering and producing concrete has at least two important implications. First, it severely constrains a concrete producer's ability to minimize the GHG footprint of concrete used in any given project. Second, it serves as a broad-based disincentive for the concrete industry to use its substantial expertise to innovate and create new products.

By accelerating the transition toward specifications that focus on the *performance* characteristics of the product, policymakers have an opportunity to enable and empower concrete producers to design and deliver products that meet customer needs while minimizing embodied emissions. Equally as important, a re-orientation toward performance-based specifications would provide the concrete industry with more flexibility and incentive to create innovative, lower carbon mixes that will accelerate the path to net zero.

It is important to note that a transition toward performance-based specifications is not only a discrete decarbonization pathway, but also an enabler of other pathways. For instance, the concrete industry's ability to reduce the GHG footprint of concrete by expanding the use of lower carbon cement, expanding the use of supplementary cementitious materials, and optimizing the design of concrete mixes would all be aided and accelerated by a shift toward performance-based specifications.

Barriers to Progress

Implementing a wholesale shift to performance-based specifications cannot be achieved by the concrete industry alone as it requires buy-in from numerous downstream actors and customers. Furthermore, a rapid and impactful pivot in the way business and planning is conducted necessitates an outsized role for education and awareness in a sector that is understandably very risk averse to implementing novel techniques and mixes. Driving meaningful reductions in concrete's embodied GHGs with performance-based specifications is not possible without efforts to address these headwinds.

Predictability is the primary customer concern with a switch to performance-based specifications. Although low GHG concrete mixes can meet the same performance metrics as other lower water-to-cement ratio concrete mixes, most actors on the design and construction side of the value chain understandably prioritize safety, speed, familiarity, and proven performance. While increased communication between concrete industry actors and designers, engineers, and specifiers can help bridge the gap, uncertainty around liability, insurance, and other factors means that any deviation from the status quo will likely be much more complicated than a simple switch away from prescriptive specifications.

Pathway 2

Use Less GHG Intense Raw Materials

The vast majority of concrete's carbon footprint stems from the ingredients used to make it, particularly cement. Accordingly, achieving net zero concrete hinges on substantially reducing the carbon intensity of those ingredients through some combination of: (1) utilizing lower carbon cements; and (2) utilizing SCMs.

Lever 2.A: Expand the Use of Lower Carbon Cements

The Opportunity

Although cement makes up a small share of concrete by volume, it accounts for roughly 90% of concrete's embodied emissions. As such, while activating the other levers described in this roadmap is important and necessary, the ability of the concrete industry to meet the goal of carbon neutrality by 2045 hinges on the availability of lower carbon cements.

The California concrete and cement industries are on aligned and parallel paths to carbon neutrality. For instance, the cement industry has released a comprehensive roadmap detailing how to achieve net zero by 2045, and legislation (SB 596) has been enacted to develop a sector-specific strategy to achieve carbon neutral cement on the same timeframe. This roadmap builds on the cement industry's vision and expands on it to consider opportunities and barriers further down the supply chain.

Notably, the transition toward lower carbon cements is already in progress. Caltrans recently approved the use of Portland Limestone Cement (Type 1L), which has the potential to reduce the GHG emissions footprint of concrete by up to 10%.[13] Although it will take time for Portland Limestone Cement to reach full market penetration and potential, its introduction into the California market has not only sparked a conversation around the benefits of lower carbon cements but also paved the way for increasingly innovative, lower carbon mixes on the horizon.

Barriers to Progress

Producing carbon neutral cement entails a wide range of practical, regulatory, and economic barriers to rapid and meaningful decarbonization. The external conditions facing the California concrete industry create an environment in which carbon neutrality is out of reach without a significant increase in cement industry investment in decarbonization or a meaningful shift in customer preferences and design/engineering best practices.

- **The Challenge of Producing Low Carbon Cement:** Decarbonizing cement is a unique challenge due to the presence of process emissions — the unalterable result of the chemical reaction that converts limestone to make cement. Process emissions account for almost two thirds of all emissions associated with cement manufacturing and cannot be mitigated via traditional methods (e.g., fuel switching, energy efficiency).[14] Although the responsibility to produce low carbon cement falls outside of the scope of the concrete industry, it is an essential input to achieving carbon neutral concrete in California. Diverse and significant technical, regulatory, policy, and cost barriers negatively affect cement industry decarbonization efforts and make access to lower-carbon cements the single greatest obstacle to achieving carbon neutral concrete in California by 2045.
- **Costs:** Significant decarbonization of cement and, by extension, a carbon neutral cement-concrete-construction value chain, will be unattainable without widespread deployment of carbon capture, utilization, and storage (CCUS) technology. CCUS technology is incredibly costly and is an emerging technology that has not yet hit industrial scale viability in the cement industry. Without significant public funding or other assistance to support investment in efforts to decarbonize cement manufacturing — including CCUS

but also extending to alternative fuels, novel raw materials, and cement plant upgrades — the availability of low carbon cements implies a much costlier product in the near-term.

- **Education and Awareness:** At present, many concrete industry customers are not aware of the benefits of specifying lower-carbon cements, and designers, architects, and engineers often overestimate the performance tradeoff between the status quo and lower-carbon concrete mixes. As a result, customers typically default to traditional concrete with recognized and customary performance characteristics. This lack of education and promotion among customers and specifiers poses a formidable barrier to rapidly increasing the adoption of concrete made with lower-GHG cements.

Lever 2.B: Expand the Use of Supplementary Cementitious Materials

The Opportunity

SCMs are materials with cementitious properties that can be added to concrete, either at the cement plant or ready-mix batch plant, as a replacement for cement. Effectively, SCMs reduce embodied emissions in concrete by partially replacing emissions-intensive cement with less emissions-intensive raw materials while maintaining specified performance characteristics.

To delineate between SCMs derived from industrial processes and those mined and processed from geological formations, for the purpose of this report, SCMs are divided into two main categories: end-of-life materials and alternative raw materials.

End-of-life materials are the byproduct of other, unrelated industrial processes with cementitious properties that can reduce the need for cement in a concrete mix. While there are many unique SCMs with varied impacts on emissions, the end-of-life materials of most interest to the California concrete industry include:

- **Fly Ash:** Fine ash captured during combustion at coal-fired power plants. This SCM can theoretically replace up to 40 to 50% of cement in concrete.[15] Fly ash is currently the most widely used SCM in concrete manufacturing. However, the continued trend away from coal-fired electricity generation constrains the availability of fly ash — a trend that is expected to accelerate in coming years. To counteract supply challenges, the industry is exploring opportunities to recover fly ash from other sources — ash ponds, landfills, etc.
- **Ground Granulated Blast Furnace Slag (GGBS):** Byproduct of steel manufacturing created by quenching molten blast furnace slag with water or steam. GGBS can replace up to 50 to 70% of cement in concrete.[16] GGBS is currently a widely used and accepted SCM; however, the availability of GGBS in California is likely to decrease in the future due to both a decrease in the global supply and an increase in the global demand for the product in a carbon-constrained world.
- **Silica Fume:** Fine powder byproduct of silicon and ferrosilicon alloy manufacturing, used to create a higher strength, lower porosity concrete.[17] Silica fume can theoretically replace up to 25% of cement in concrete, but due to issues with curing time and strength development, no more than approximately 10% of cement can be replaced without negatively impacting the quality of the concrete.[18] While silica fume use is increasing, it is most often used to create higher strength, lower porosity concrete than as a means to reduce its carbon footprint. Regardless of the use case, any silica fume blending will result in a lower GHG profile than concrete without SCMs.

In contrast to end-of-life materials, alternative raw materials (ARMs) are geologically derived materials that are extracted and processed for direct use in concrete or cement. The ARMs with greatest potential to reduce embodied emissions in concrete in California include:

- **Natural Pozzolans:** Locally abundant, volcanic ash deposits that can be mined and ground to create an SCM. While currently in the developmental stage, natural pozzolans have a high potential for future, widespread deployment and associated GHG impact.[19]

- **Calcined Clays:** Naturally occurring clays that are heated to high temperatures (calcined) and ground for use as an SCM. Most calcined clays used by the industry are derived from kaolin clays, which have the potential to replace 20-30% of cement in concrete, in addition to favorable strength and porosity characteristics.[20,21]

Certain chemical admixtures can be used to adjust the performance, characteristics, or composition of concrete to unlock higher rates of SCM substitution. For instance, superplasticizers can be added to reduce the water-to-cement ratio and enhance workability without sacrificing performance, which, in turn, reduces cement requirements. In a GHG mitigation context, “superplasticizers” can reduce the amount of cement in a unit of concrete by allowing for greater replacement of SCMs without sacrificing performance.[22] As another example, “accelerators” can be added to increase early strength development of concrete as it sets. When used in conjunction with a superplasticizer, accelerators reduce the early strength development issues that higher rates of SCM substitution can cause.[23]

As a general rule, the GHG impact of SCMs is roughly proportional to the amount of cement replaced by these materials.[24] The actual GHG savings, however, can vary by use case, specifications, and SCM type. According to reports released by other cement and/or concrete industry associations, an SCM blending rate of at least 25% across all concrete produced will be needed to put carbon neutrality by 2050 within reach.[25,26] Higher replacement rates may be possible as emerging SCMs and novel blends of more than one SCM — for example, blends of fly ash and natural pozzolans — enter the market, but regardless, creating an environment that enables high levels of SCM substitution will be essential to achieving net zero concrete in California.

SCM Substitution Throughout the Value Chain

SCMs can either be added at a ready-mix concrete batch or manufacturing plant, or preblended with cement before delivery to the batch plant. In either case, adding SCMs will have the same impact on the embodied carbon of concrete. In California, SCMs are primarily added by concrete manufacturers rather than at cement plants, where most of the global concrete value chain adds SCMs. Differences in up- and down-stream relationships make it difficult to compare the California concrete industry with global peers. It is critical for policymakers to understand the intricacies of the cement-concrete-construction value chain and facilitate SCM usage — regardless of who adds the SCMs.

Barriers to Progress

Although rapidly reducing the average cement content of concrete with SCMs remains one of the most cost effective and impactful decarbonization levers available to the California concrete industry, realizing the full potential of SCMs requires navigating a host of supply, infrastructure, and technological challenges. To remain on pace with carbon neutrality goals, the California concrete industry will need to rapidly increase the average ratio of SCMs to cement in concrete from approximately 5% to at least 25% — a goal that will require access to roughly 3 million metric tons (MMT) of SCMs annually by 2045.[27]

- **SCM Availability:** Access to GGBS and fly ash — the most used and widely accepted SCMs — is rapidly dwindling as the global steel industry switches from blast to electric arc furnaces and coal-fired power plants are shuttered. In fact, the global supply of GGBS and fly ash is expected to decline 16% (relative to 2018 cement production) by 2050.[28] While increasing the use of SCMs is a point of emphasis for the global concrete industry, the industry is at a challenging inflection point where SCM supply is insufficient to meet demand, and natural SCMs that can alleviate supply issues are not yet ready for widespread deployment.

- **Admixture Cost:** The upfront costs of admixtures, such as superplasticizers, are often prohibitively expensive for use in residential and other small-scale projects. However, over the full lifetime of a structure, the increased durability and lower maintenance costs of concrete made with these admixtures offset the increased costs when used at scale. Accelerator admixtures are also relatively expensive, although their impact on a project budget is somewhat offset by the lower labor costs associated with reduced setting times.
- **Infrastructure Constraints:** Limited storage capacity and infrastructure at batch plants stymy the use of SCMs and will require significant additional investment to address. Designing lower GHG concrete blends requires the ability to add uncontaminated and precise amounts of raw materials in accordance with customer specifications, which are often dictated by a mix of regulations, best practices, and performance or appearance preferences. Due to high capital cost requirements — capital costs of adding a silo to a batch plant range from $50,000 to over $1M per silo — most concrete batch plants only have one or two silos to store SCMs.[29] Without additional silos for storage capacity, managers will be limited in their ability to unlock the full potential of SCMs to craft lower GHG concrete mixes.
- **Research, Development, & Deployment:** Offsetting the looming GGBS and fly ash supply crunch requires ramping up availability and creating new supply chains for naturally occurring SCMs. Despite California's abundant pozzolan deposits, heavy regulatory requirements and high costs pose barriers (e.g., permitting for new mining facilities, installing new infrastructure) to establishing and building what would essentially be an entirely new supply chain, including sourcing, mining, transportation and storage, and research and development (R&D) efforts.
- **Strength Development Requirements:** Currently, the standard maturity age for concrete strength development is 28 days. Although concrete with no SCM substitution will result in earlier strength development, concrete produced with SCMs often, at later ages of maturity, offers the same or better concrete performance. As a result, current standards discourage SCM substitution and result in higher GHG concrete. While the optimal age to maturity will vary by application, certain applications (e.g., foundations) would particularly benefit from specifying longer strength development times to enable greater SCM substitution.

Pathway 3

Optimize Design, Reduce Waste, & Increase Circularity

Production of unused concrete or concrete that is returned as waste represents a missed opportunity to lower the GHG footprint of the California concrete industry. Additionally, capitalizing on opportunities to divert demolished concrete from landfilling to reuse can, where applicable, further reduce industry GHG emissions. The concrete industry can reduce industry-wide emissions by: (1) optimizing concrete use; and (2) increasing industry-wide circularity.

Lever 3.A: Optimize Concrete Use

The Opportunity

Optimizing concrete use to avoid overdesign and reduce waste can yield meaningful emissions savings.

- **Avoiding Overdesign:** California concrete producers do not directly own, develop, or change design practices, building codes, and specifications. However, they can play an important role as educators to help customers fully understand the GHG implications of different designs, avoid overdesign practices that result in more cement in the concrete mix than is necessary to meet a customer's needs, and account for use-phase factors that can influence performance requirements. The Portland Cement Association estimates that more efficient use of concrete in construction can reduce overall U.S. concrete emissions by 30% by 2050, though the actual GHG benefits of optimizing design will vary from mix-to-mix and depend on local conditions.[30]
- **Reducing Waste:** On average, approximately 5% of concrete delivered to a job site is returned unused.[31] Although this concrete can often be recycled or downcycled, avoiding this waste altogether would have a much greater impact on overall industry emissions. This overordering is in part due to uncertainty and helps manage the risk that a certain portion of concrete may be unusable and to mitigate logistics, supply, and availability issues that can result in project delays and increased labor costs.

Obviously, the California concrete industry does not have the ability to directly influence design and construction practices. However, it does have an important role to play in working with customers to understand their needs and, whenever possible, offering options for reducing the GHG emissions associated with concrete while achieving performance objectives.

Barriers to Progress

Given that optimizing the demand for concrete is well outside the industry's sphere of influence, an accounting of the policy, regulatory, and behavioral barriers that hinder progress on this front is well outside the scope of this report. That being said, finding opportunities to avoid overdesign and reduce waste will be critical to achieving net zero concrete in California, and the concrete industry is prepared to play its part as one of many stakeholders (architects, engineers, contractors, developers, owners, policymakers, regulators, etc.) that will need to come together to address those barriers and meaningfully change current design and construction practices.

Lever 3.B: Increase Circularity

The Opportunity

The concrete industry is an important link in an increasingly circular economy. By reusing demolished or waste concrete to reduce the need for “fresh” raw materials in subsequent concrete mixes, the industry can reduce its embodied carbon footprint and provide beneficial uses for building materials that would otherwise be landfilled.

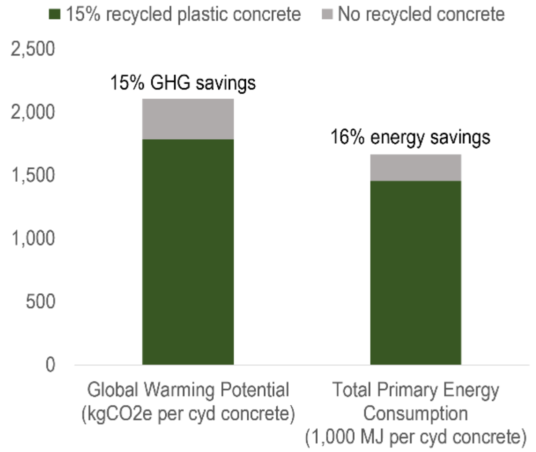
There are two important terms to keep in mind when evaluating the opportunities to reuse concrete: recycling describes reusing concrete for the same end-use while downcycling describes the reuse of concrete for more limited uses than the original material.[32] Both practices will be critical to helping the concrete industry be an even more important contributor to the circular economy and reducing the GHG emissions associated with California’s consumption of concrete.

- **Recycling:** Although processing hardened (either end-of-life or returned by customers) or plastic (“fresh”) concrete to make materials that can be recycled into new concrete is a relatively new effort, avoiding the emissions associated with the raw materials in virgin concrete can have a significant impact on embodied emissions. Compared to current concrete crushing technology used to downcycle materials, new smart crushing technology is in development that can break concrete into its constituent ingredients.[33] Because not all of the cement used in a concrete mix reacts with water, a portion of the cement recovered through smart crushing methods can be used directly in virgin concrete, along with recovered sand and coarse aggregates, to avoid a substantial share of overall embodied emissions.[34]
- **Downcycling:** A significant portion of concrete cannot be easily recycled and redeployed to meet the same end use. Without efforts to increase circularity, the concrete will simply be placed into a landfill.[35] However, demolished or waste concrete can often be used as a base or a coarse aggregate in subsequent structures, thereby avoiding the emissions associated with aggregate extraction, process, and transportation. Often, downcycling concrete to aggregates and road base is affordable, common, and already standard industry practice in many markets across the world.[36] Expanding the GHG reduction potential of this lever involves increasing the use of downcycled concrete even further and finding new structural uses for these materials.[37]

Barriers to Progress

Using crushed concrete for road base is an established practice around the world and faces no systemic barriers in California. However, expanding the beneficial end uses of waste or demolished concrete to substantially reduce the emissions footprint of the California concrete industry faces a more challenging path to widespread deployment. Realizing the full decarbonization potential of this lever requires addressing cost and technological barriers, as well as educating stakeholders throughout the value chain.

Figure 3. GHG And Energy Impact of Recycling Plastic (Fresh) Concrete



Betita, R. (2013). Environmental Impacts of Recycled Plastic Concrete. Climate Earth. (link)

- **Cost:** While downcycling concrete is relatively cost effective, downcycled concrete (unlike recycled concrete) does not eliminate the need for cement in subsequent concrete mixes. However, the technology needed to yield usable recycled raw materials is expensive and not yet widely available. Maximizing the decarbonization potential of recycling will require substantial investments of public and/or private funds to increase the number of smart crushers capable of recycling concrete in California.[38]

- **Logistics:** Due to the added cost, emissions, and logistical challenges of transporting demolished and waste concrete, processing concrete for downcycling and recycling is most effective when accomplished on a job site and used immediately.[39] However, concrete batch plants, from a decarbonization perspective, would be better equipped to use recycled or downcycled concrete to reduce the industry's embodied emissions. Navigating a path to efficient (both in terms of cost and GHG emissions) distribution and processing of demolished and waste concrete will require greater collaboration between the concrete industry and downstream stakeholders, as well as the ability to transport materials using low emissions means.
- **Awareness:** Not accounting for the emissions impact, the most cost effective and beneficial use of demolished concrete is to simply crush it and use it as road base. More than 98% of downcycled concrete is used for this purpose.[40] On the other hand, maximizing the decarbonization potential of this lever implies greater recycling and use of downcycled concrete for other structural uses (e.g., coarse aggregates). Making this shift will require greater awareness across the entire cement-concrete-construction value chain to make sure concrete is being used for the most impactful end use available.
- **Performance:** The chemical properties of downcycled concrete reduce the potential to use these materials as aggregates for structural concrete. Downcycling does not break concrete up into its constituent ingredients, but instead produces a coarse aggregate that includes reacted cement and sand, as well as residual coarse aggregate. Primarily due to the presence of reacted concrete, this results in diminished and variable performance when used for structural applications, as opposed to concrete used for roads and road base.[41] In order to expand the use of downcycled concrete, techniques to remove adhered cement from downcycled concrete will need to be developed and deployed.

Pathway 4

Increasing the GHG Efficiency of Concrete Operations

Up to 10% of the total embodied emissions in a unit of concrete are comprised of emissions associated with manufacturing — primarily indirect emissions from electricity use — and transportation.[42] In the long-term, the availability of net zero emissions electricity can reduce most of these emissions — a goal the state intends to achieve by 2045. However, in the near-term, the California concrete industry can reduce emissions stemming from these activities through two primary levers: (1) automating concrete manufacturing operations and (2) decreasing transportation emissions.

Lever 4.A: Automate Concrete Manufacturing Operations

The Opportunity

The California concrete industry has taken the necessary first step of electrifying concrete batching operations and, by implementing measures to increase the energy efficiency of concrete manufacturing operations in California, can reduce the embodied emissions in concrete associated with electricity generation. The industry has been automating processes for many years, so the potential impact could be low. In addition, given that the state is on a statutory path to net zero electricity generation (SB 100), improving energy efficiency is mostly — from an emissions perspective — an interim measure.[43] However, any gains to efficiency will have the long-term effect of reducing industry consumption of zero carbon electricity to free up resources for other end uses.

Investing in systems that increase automation, optimize raw materials procurement, and increase the accuracy of concrete mixes are all examples of process improvements that can increase efficiency and, by extension, GHG performance. There are many systems and services on the market that can streamline operations, reduce waste, and provide end-to-end tracking and monitoring of batching operations from raw materials procurement to pouring mixed concrete. Enhanced monitoring and mixing also has the potential to streamline the development of environmental product declarations (EPDs) and afford ready-mix producers greater flexibility to generate EPDs for new or one-off mixes without having to seek costly analysis and verification from a third party.[44]

When operationally and economically feasible for a manufacturer, automating manual batching operations and raw materials procurement enables more precise management of resources, output, and operation, as well as limiting the potential for operator error or misjudgment that can result in unusable or excess product. Widespread use of these systems throughout the California concrete industry can provide meaningful emissions reductions on the path to carbon neutrality.[45]

Barriers to Progress

Although automated batching technology is widespread and available, the diverse nature of the California concrete industry means that the benefits — and costs — of installing automated batching infrastructure may not be feasible in all cases. The benefits of deploying this lever may not be felt evenly across all companies and plants and may not offer the same relative improvement in GHG performance as compared to other decarbonization measures.

- **Scale:** Typically, the larger the batch plant, the greater the emissions benefit of automation. However, California's concrete industry is comprised of hundreds of companies and batch plants of assorted sizes and levels of sophistication. As a result, automating batch plant operations is not a "one-size-fits-all" solution and the investment required may not justify the benefits for many plants — especially when compared to other decarbonization levers that have the same relative impact on emissions regardless of plant scale.

- **Operational Concerns:** Retrofitting existing batching equipment with the technology to automate operations may entail production shutdowns for installation, testing, and calibration. The level of sophistication and the footprint of associated equipment varies from system to system. However, shutting down production to install new systems may cost more in terms of lost output than the benefits gained by automating operations. Additionally, some batch plants may have already achieved maximum efficiency or do not have sufficient energy capacity to power new infrastructure.

Lever 4.B: Decrease GHG Emissions from Concrete Industry Transportation

The Opportunity

Transporting raw materials to batch plants and concrete to job sites makes up — excluding emissions from cement manufacturing — a meaningful share of the embodied emissions per unit of concrete. Transitioning to fleets fueled by zero- or low-emissions energy sources can reduce industry transportation emissions to zero by 2045.

There are a variety of fuels and technologies that can achieve this goal. The main fuels of interest to the concrete industry include:

- **Compressed Natural Gas (CNG) / Renewable Natural Gas (RNG):** Natural gas — either fossil natural gas or RNG — is an attractive fuel to provide lower carbon energy to California concrete industry fleets. Relative to diesel, even fossil CNG would have a substantial impact on industry transportation emissions, and ready-mix producers in California have already made meaningful progress towards decarbonizing their fleets using this lever. Taking this shift one step further to the widespread use of RNG — methane, typically captured from dairy or landfill operations and upgraded to match the properties of fossil natural gas — can make concrete industry fleets carbon neutral, or even carbon negative in some cases. Although increasing the use of RNG faces significant challenges (see “The Barriers” section), the technology is mature and ready for deployment without additional investments in research and development.[46,47]
- **Electricity:** Vehicle manufacturers are actively working on efforts to produce reliable all-electric concrete mixers to match the unique circumstances of the concrete industry.[48] However, due to the energy required to transport and mix tons of product at a time, it is unlikely that electrifying concrete industry fleets will be feasible in the near-term. As battery capacity increases, it is possible that electric concrete mixers will be a viable option for concrete industry fleet decarbonization in the future — although their use will likely be limited to batch plants that typically deliver concrete in their immediate local area.
- **Renewable Diesel:** Renewable diesel is an emerging fuel that can be manufactured using most biomass feedstocks. Renewable diesel can replace 100% of fossil diesel use and can be used directly in existing diesel fleet vehicles, providing a low carbon “drop in” fuel to power concrete logistics.[49,50]

The California Air Resources Board (CARB) recently adopted an Advanced Clean Fleets regulation specifying a path to zero emissions commercial fleets by 2045.[51] Although the regulation specifies hydrogen or electrification technology as the eventual goal, renewable diesel and CNG/RNG will play a role in the transition to 100% clean fleets. On the path to net zero, the Advanced Clean Fleets regulation will likely accelerate concrete industry deployment of low and zero emissions vehicles.

Barriers to Progress

Market and technological barriers limit the feasibility of fleet decarbonization with alternate fuels. The deployment of industry-ready alternative fuels is stymied by cost, availability, and technical limitations that likely cannot be tackled without significant and rapid financial and policy support.

- **Cost:** Low or zero carbon alternative fuels, like RNG and renewable diesel, suffer from high production costs that make switching to these fuel sources uneconomical in the short term. As an example, although the Low Carbon Fuel Standard (LCFS) has reduced the cost of RNG, upgrading gas from dairy digesters or landfill methane to fossil natural gas performance remains, in most cases, prohibitively costly.[52] Even with public subsidy programs, RNG is a long way off from being cost competitive with fossil natural gas. In the case of electric mixing vehicles, switching to electric mixer fleets when available will require purchasing brand new fleets of high-cost vehicles, establishing new infrastructure at batch plants, and increasing the risk of stranding prior investments in transportation decarbonization (e.g., CNG mixers) on the road to carbon neutrality.
- **Availability:** RNG and renewable diesel producers face a challenging path to reaching a scale that enables widespread deployment of low carbon alternative fuels. The challenges that renewable diesel producers face provide an illustrative example of the acute supply issues preventing production at scale. While renewable diesel can use a flexible range of biomass feedstocks, greater demand for these feedstocks to produce other alternative fuels has created a challenging landscape where low carbon fuel producers compete for limited resources — a problem that is further compounded as demand for these fuels increase. Additionally, the capital costs required to either build new refining facilities or retrofit existing petroleum facilities limits the probability that renewable diesel will be available for widespread use by California concrete industry fleets without substantial incentives or public support.[53]
- **Technical and Raw Material Limitations:** Electrifying heavy-duty vehicles presents many technological challenges. For example, the weight and energy consumption of concrete mixers limits the maximum operational range of electric mixers, and similarly, large batteries limit the volume of material that can be transported. Furthermore, the same raw materials constraints that prevent the deployment of passenger electric vehicles affect the deployment of heavy-duty electric vehicles.[54] Until heavy-duty electric vehicle producers can overcome these challenges, it is unlikely that the California concrete industry will be able to initiate a concerted effort to switch to electric fleets.[55]

Pathway 5

Increase the Recarbonation Potential of Concrete

The Opportunity

Recarbonation refers to the natural absorption of CO_2 from ambient air by concrete structures. The emissions mitigation potential of this lever depends on many factors (e.g., local weather, paints, coating, design), which can all influence use-phase uptake of CO_2 and, as a result, the scientific community has not developed a full accounting of the true impact of recarbonation. Nevertheless, by incorporating best practices to increase the potential uptake of CO_2, the concrete industry can reduce the emissions impact of concrete over the use and end-of-life phases of the concrete lifecycle.

- **Use Phase Best Practices:** Increasing the recarbonation potential of concrete involves complicated tradeoffs between climate benefits and structural integrity. For example, reinforced concrete is inherently designed to limit recarbonation since, if carbonated concrete comes into contact with steel rebar, the rebar can corrode and result in cracking or warping. However, unreinforced concrete actually increases in strength with recarbonation. Other factors influencing recarbonation potential include coatings, building design, and mix design.[56] For example, an unpainted concrete building made of concrete with a high share of SCMs will inherently absorb more CO_2 over the use phase than a painted structure made with high strength, low SCM concrete. While these factors are often out of the concrete industry's control, the industry can help drive customer awareness about design mixes that are optimized for recarbonation while maintaining specified performance characteristics.
- **End-of-Life Best Practices:** Once a building is demolished, with proper handling to maximize CO_2 uptake, waste concrete can absorb significant amounts of CO_2. End-of-life best practices to increase recarbonation potential include crushing demolished concrete and storing it with maximum surface area exposed to ambient air or using crushed concrete as a road base.[57] For example, if crushed concrete is used as road base, the end-of-life concrete will continue to absorb CO_2 while serving another beneficial use.

Barriers to Progress

Increasing recarbonation in concrete is largely outside of the control of the concrete industry and hinges on action by downstream actors such as project developers, architects, and engineers. Furthermore, the current regulatory and scientific environment is not set up to recognize CO_2 sequestered through recarbonation or provide discrete estimates of GHG reduction impact. Without removing these barriers and giving the concrete industry credit for naturally absorbed CO_2, carbon neutrality targets will likely remain out of reach, and an important source of GHG sequestration will be under-utilized.

- **Regulatory Barriers:** Recarbonation has only recently emerged as a significant factor in estimating the CO_2 impact of concrete. As result, there is currently no definitive system or framework to account for CO_2 absorption in environmental product declarations (EPDs) or emissions regulations. At present, standard EPDs account for emissions from "cradle to gate" and do not account for emissions mitigated during use phase and end-of-life recarbonation. In a California context, the true embodied emissions profile is not reflected in the state's GHG monitoring program since recarbonation is not included in emissions accounting. Without efforts to measure and give credit for emissions mitigation outside of the batch plant, the concrete industry will face an unnecessarily difficult path to carbon neutrality when evaluated through the lens of current GHG accounting standards.
- **Uncertainty:** Estimating the embodied emissions of concrete from "cradle to gate" is a relatively straightforward and standardized task with years of scientific consensus to support measurements. In comparison, recarbonation varies across climates, concrete uses, mixes, and

building designs — just to name a few drivers of CO_2 absorption. Although the scientific community is getting closer to a viable framework to account for recarbonation, applying a standard measure of recarbonation potential is likely to continue to complicate efforts to measure and give credit for concrete CO_2 uptake.

- **Outside the Industry's Sphere of Influence:** Most of the actions that can be taken to maximize the impact of this decarbonation lever are entirely out of the control of the concrete industry — such as building design, reinforcement, and demolition. For example, as long as reinforced concrete remains the norm for buildings, the concrete industry will continue to provide concrete that seeks to minimize potential corrosion and, by extension, carbon uptake. As a result, without customer preferences in favor of maximized recarbonation, the concrete industry cannot fully capitalize on the potential of concrete as a carbon sink.

Policy Recommendations

1. **Support efforts to move toward performance-based concrete specifications** to grant concrete producers the flexibility to meet desired performance characteristics through the lowest GHG option available, rather than designing mixes to meet prescriptive specifications.
2. **Support incentives to lower the cost of novel low carbon concrete technologies** to spur customer demand for impactful, yet costly, breakthrough technologies.
3. **Provide public support to de-risk industry investment** in plant upgrades and new infrastructure needed to decarbonize concrete production.
4. **Establish incentives and other programs** (e.g., stakeholder education) to spur market demand for concrete mixes with high shares of SCMs — especially blends utilizing locally abundant natural pozzolans.
5. **Provide public financing and investment support** for infrastructure upgrades at batch plants that can expand the use of SCMs (e.g., new silos).
6. **Convene relevant stakeholders** to create new circular supply chains that incorporate demolished concrete and allow the concrete industry to fulfill customer orders with materials that further maximize recarbonation of end-of-life concrete.
7. **Amend construction and design regulations** to enable the concrete industry to produce mixes that increase the recarbonation potential of concrete.
8. **Establish public-private RD&D partnerships** to de-risk private investment in projects to develop new sources of ARMs (e.g., natural pozzolans and calcined clays) and rapidly bring them to market.
9. **Encourage increased collaboration** between the concrete industry and downstream customers (e.g., project owners, specifiers, and contractors) to produce concrete that meets customer needs while also optimizing the GHG footprint of a project or structure.

Conclusion

Achieving carbon neutrality without undue delay calls for a flexible approach that recognizes industry realities and actively seeks to clear barriers to the deployment of decarbonization levers. Such an approach is essential due to the diverse size and structure of the companies that make up the California concrete industry. With flexibility and choice, individual plants and companies can chart a path to decarbonization that matches their unique circumstances. Achieving this goal will require active cooperation between the industry and a diffuse network of stakeholders over the entirety of the cement-concrete-construction value chain to create an environment conducive to rapid investment in GHG mitigation. Reaching carbon neutrality by 2045 is a daunting challenge, and the concrete industry has little unilateral control to create such a sweeping change. However, the combined effort of the industry, policymakers, regulators, and other stakeholders can unlock viable pathways to advance the solutions to the barriers outlined in this report and achieve carbon neutrality by 2045.

Endnotes

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[1] United Nations Intergovernmental Panel on Climate Change (2022). IPCC Sixth Assessment Report: Summary for Policymakers. United Nations. https://www.ipcc.ch/report/ar6/wg2/chapter/summary-for-policymakers/

[2] For the purposes of this report, "concrete" refers primarily to ready-mixed concrete, which is the primary means of producing concrete. CALCIMA members account for the vast majority of ready-mixed concrete that is produced, sold, and used in California.

[3] Portland Cement Association (n.d.) Shaped by concrete: building safer, stronger communities. https://www.shapedbyconcrete.com/#news?article=building-communities

[4] Brown, D., Durschlag, H., Hsu, S.L., Love, A., Norford, L.K., Ochsendorf, J., Santero, S., Swei, O., Webb, A., & Wildnauer, M. (2011). Methods, Impacts, and Opportunities in the Concrete Building Life Cycle. Massachusetts Institute of Technology Concrete Sustainability Hub. http://cshub.mit.edu/sites/default/files/documents/MIT%20Buildings%20LCA%20Report.pdf

[5] Labor Market Information Division (2022). Quarterly census of wages and employment: ready-mix concrete manufacturing. state of California employment development department. https://data.edd.ca.gov/Industry-Information-/Quarterly-Census-of-Employment-and-Wages-QCEW-/fisq-v939

[6] Ibid.

[7] For each yard of returned concrete that can be re-used, there is a 15.3% reduction in carbon footprint, according to a Caltrans report. The adoption of the standard by Caltrans was followed by international code setting agencies establishing standards to allow for up to 50% returned concrete in concrete mixes (link).

[8] Whether water recycled from their own operations or municipal sources of recycled water, this saves large amounts of water and energy.

[9] Brown, D., Durschlag, H., Hsu, S.L., Love, A., Norford, L.K., Ochsendorf, J., Santero, S., Swei, O., Webb, A., & Wildnauer, M. (2011). Methods, Impacts, and Opportunities in the Concrete Building Life Cycle. Massachusetts Institute of Technology Concrete Sustainability Hub. http://cshub.mit.edu/sites/default/files/documents/MIT%20Buildings%20LCA%20Report.pdf

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[11] For the sake of simplicity and as a practical matter, this report does not consider indirect emissions associated with the consumption of electricity. Per SB100, all electricity used in California will be carbon neutral by 2045 and, as a result, emissions associated with electricity consumption are not expected to contribute to the emissions footprint of California concrete in the long term.

[12] National Ready Mix Concrete Association (2022). Ready Mixed Concrete Production Statistics, 1998 – 2021, California. https://www.nrmca.org/association-resources/nrmca-surveys-benchmarking/

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