LOW CARBON CEMENT PRODUCTION

ISSUE PAPER

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This issue paper, initially developed by ClimeCo LLC, is for use by the Climate Action Reserve in the development and evaluation process for a standardized offset project protocol reducing emissions from low carbon cement production.

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Executive Summary

The Climate Change Impact of Cement

Cement production is one of the largest sources of greenhouse gas (GHG) emissions in the industrial sector and contributes to approximately 8% of human-caused global carbon dioxide (CO_2) emissions. The majority of GHG emissions from producing the most common type of cement, known as ordinary portland cement (OPC), are attributable to a chemical reaction caused by a high-temperature process ("calcination") used to produce clinker, the primary intermediary component for OPC. The remainder of the emissions from cement production result from burning fossil fuels to create the heat required for calcination and the mining and transportation of the materials used during the production process.

Cement is a key binding agent in concrete, the most widely used building material in the world. The need for new buildings and infrastructure is expected to lead to an increase in the demand for cement through mid-century and beyond. This issue paper was developed to evaluate the potential for carbon financing to support GHG emission reductions in the cement and concrete manufacturing industries by incentivizing clinker replacement and substitutes to OPC.

About Supplementary Cementitious Materials

One of the main strategies to reduce GHG emissions associated with cement production is to reduce the amount of OPC used in manufacturing concrete by replacing some or all of the OPC with alternative materials called supplementary cementitious materials (SCMs). SCMs can be used to improve performance and reduce clinker content by either replacing OPC at the cement processing plant to form blended cement or, as more commonly seen in the United States, adding SCMs at the ready mix concrete plant to produce SCM concrete. The most well-known SCM in today's market is fresh fly ash, a byproduct of the coal-fired power generation, which is significantly limited in the United States. The next most well-known SCM is ground granulated blast furnace slag (GGBFS), a byproduct of crude iron production, which remains available only in certain geographical regions. Silica fume, metakaolin, and some natural pozzolans have also been used as OPC replacements, albeit in relatively small amounts.

Barriers to Increased SCM Use

In the United States, the availability and usability of SCMs, and thus the potential for GHG emission reductions resulting from their use, are limited by numerous market, institutional, financial, and technical barriers.

First, there is an inadequate and shrinking supply of usable SCMs to meet the growing demand. The two most used types of SCMs, fresh fly ash and GGBFS, are produced as industrial byproducts at coal-fired power plants and crude iron furnaces, respectively. As the use of coal declines and some steel manufacturers adopt cleaner technologies, less byproduct SCM is regionally available, causing a significant and growing gap between supply and demand. National fly ash supply decreased by over 55% from 2010 to 2019 as coal-fired power plants closed, repowered, and became subject to more stringent emission controls that have reduced their output of usable fresh fly ash. Most of the GGBFS consumed in the US is imported from overseas as the volume of nationally produced and available GGBFS are inadequate for meeting domestic demand. Other types of SCMs - including silica fume, metakaolin, and natural pozzolans - are significantly limited by geographic availability, processing costs and, in some cases, undesired performance impacts on the final concrete product.

Second, although industry participants have experimented with innovative new categories of SCMs, these new categories face technological and economic barriers to scaling. Large quantities of fly ash of varying consistency and quality have been deposited in landfills and ash ponds. These disposed volumes could potentially be used to produce SCMs, but the methods to harvest and process the fly ash to make it suitable for concrete are economically prohibitive and in the early technological stages. Industry participants have also been pilot testing the use of natural pozzolans by applying innovative combinations of natural materials and processing techniques; however, these processes are costly and are not ready to be deployed at scale. Innovative SCMs, including harvested and processed fly ash and processed natural pozzolans, could help overcome the SCM supply gap if technological and economic barriers can be overcome.

Third, while some SCMs may be more cost effective than OPC, the additional financial burden of transporting, storing, and processing SCMs to meet industry standards – which favor OPC – make SCMs less attractive to most producers.

The concrete and cement industry will require innovative yet costly technological advancements to bring new SCMs to market and fill the growing gap between supply and demand. Technological advancements could allow for recovering of novel SCMs (e.g., new natural pozzolans) as well as harvesting and processing currently unsuitable SCMs (e.g., landfilled fly ash) to meet specifications for concrete production. Carbon financing through offset sales can help the notoriously hard-to-abate cement sector to overcome barriers that prevent the scaling of innovative technology required for novel SCMs to enter the market.

Protocol Composition and Considerations

The protocol considered in this issue paper would incentivize increased SCM replacement for OPC, primarily through the production of new SCMs or existing SCMs that are unsuitable for use without retrieval and/or processing in the US. Several topics will require refinement and represent key decision points during protocol design, including:

1. Additionality: We recommend requiring the project to process potential OPC replacements in a way that brings new and emerging SCMs to market, such as harvested and processed fly ash and natural pozzolans. In light of the significant and growling national SCM supply shortage, any innovative SCMs that fill the growing supply void are above business-as-usual and additional.

2. Leakage: In some methodologies that consider the topic of SCM use in concrete, there is concern that leakage could occur in instances where SCM supply is low. This risk of leakage arises if projects merely shift where SCMs are used but do not increase the supply of SCMs. By contrast, this protocol will bring new SCMs to the market, thus increasing the supply of suitable SCMs. This protocol will likely not result in leakage as the amount of usable SCMs will be increased rather than diverted from one place to another.

3. Ownership: There are several parties in the chain of custody (cement producer, SCM producer, ready mix concrete producer, concrete end user) that could wish to claim ownership of the carbon offset credits. We recommend that the party processing and marketing the SCMs that replace OPC be the default credit owner to directly incentivize investments in capital and increase production of the additives, thereby bringing new SCMs to market. Contractual agreements can include chain of ownership with GHG reduction claims to ensure clarity and avoid double counting.

Table of Contents

Table of Figures

Table of Tables

Acronyms

ACCUs	Australian carbon credit units
AASHTO	American Association of State Highway and Transportation Officials
ACAA	American Coal Ash Association
ACI	American Concrete Institute
ASCM	Alternative supplementary cementitious materials
ASR	Alkali-silica reaction
ASTM	ASTM International (previously American Society for Testing and Materials)
C^3	Cool Climate Concrete
CAC	Concrete Action for Climate
$CaCO_3$	Calcium carbonate
Caltrans	California Department of Transportation
CaO	Calcium Oxide
CARB	California Air Resources Board
CCUS	Carbon capture utilization and storage
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPG	Comprehensive Procurement Guidelines
CRT	Climate Reserve Tonnes
CSI	Cement Sustainability Initiative
EIA	Energy Information Administration
EPA	United States Environmental Protection Agency
EPD	Environmental Pproduct Ddeclarations
ERF	Australia Emissions Reduction Fund
EU ETS	Europeans Union Emissions Trading System
GCCA	Global Cement and Concrete Association
GGBFS	Ground granulated blast furnace slag
GHG	Greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
K-ETS	Korea Emissions Trading Scheme
LEED	Leadership in Energy and Environmental Design
NRMCA	National Ready Mixed Concrete Association
OBPS	Canada's Output-Based Pricing System
OPC	Ordinary portland cement

PAT	India Perform, Achieve, and Trade
PCA	Portland Cement Association
SCM	Supplementary Cementitious Material
tCO_2	tonnes of carbon dioxide
tCO_2e	tonnes of carbon dioxide equivalent
USGS	United States Geological Survey
VCS	Verified Carbon Standard
WBCSD	World Business Council for Sustainable Development

Glossary

Alkali-silica reaction (ASR)	A harmful swelling reaction that occurs over time between the materials in concrete causing cracking and damage in the structure.
Blended cement	A mix of ordinary portland cement and supplementary cementitious materials that is developed at the cement plant and meets specific ASTM standards.
Cement	The binding ingredient of concrete.
Clinker	A mixture of raw materials (e.g., limestone, shale, sand, clay) that is produced in a kiln with high heat during the production of ordinary portland cement.
Concrete	A building material that is composed of cementitious materials, mineral aggregates, and water.
Finishability	The process of leveling and treating fresh concrete to create the appearance of a smooth surface.
Fresh fly ash	A by-product of coal-fired power generation that is beneficially used directly from the power plant without further processing.
Ordinary portland cement	The most common type of cement that is manufactured by grinding clinker and mixing it with other minor raw materials.
SCM concrete	Concrete that has one or more supplementary cementitious materials combined with ordinary portland cement and other materials at a ready mix concrete batch plant.
Supplementary cementitious materials (SCMs)	Siliceous or siliceous aluminous materials that can be processed to display cementitious properties and can be blended with or replace ordinary portland cement in concrete production.

Tonne	A metric unit of mass also known as a metric ton.
Workability	How easily concrete can be mixed, placed, and finished.

1. Introduction

Cement, a key binding ingredient in concrete and a critical component of the construction industry, is widely used throughout the world and represents a significant source of global greenhouse gas (GHG) emissions that contribute to climate change. The cement manufacturing industry is one of the most carbon-intensive sectors across the globe as it contributes about 2.4 gigatonnes of carbon dioxide (CO_2) emissions, or nearly 8% of anthropogenic CO_2 emissions each year.[1,2] The cement sector has experienced an annual 1.8% increase in emissions from 2015 to 2020.[3]

Cement is mixed with various raw materials including sand, gravel, and water to produce concrete and has been utilized in infrastructure and building materials since early civilization.[4] About 10% to 15% of concrete, by volume, is made up of cement.[5] Concrete represents the most used building material throughout the world and the second most utilized material, following potable water.[6]

Demand for cement is expected to increase because of the rising need for buildings and infrastructure fueled by a surge in global economic development and urbanization. By 2050, the market demand for cement is expected to be nearly 20% higher than at present.[7] This growing need is projected to continue to contribute considerably to atmospheric GHG emissions. Mitigating emissions in the cement industry will be critical to meeting the intergovernmental climate goals of limiting global temperature rise to below 1.5 to 2 degrees Celsius compared to pre-industrial levels, as outlined in the Paris Agreement.[8, 9]

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[1] International Energy Agency, "Energy Technology Perspectives 2020," *Energy Technology Perspectives*, February 2021, 400.

[2] "New Approach Suggests Path to Emissions-Free Cement," MIT News | Massachusetts Institute of Technology, accessed March 15, 2022, https://news.mit.edu/2019/carbon-dioxide-emissions-free-cement-0916.

[3] Tiffany Vass et al., "Cement," International Energy Agency, November 2021, https://www.iea.org/reports/cement.

[4] Esmeralda Shpuza and Prateek Bansal, "Considerations of a Sectoral Approach to the Cement Industry," *The Journal of Science Policy & Governance* 3, no. 1 (June 23, 2013): 37.

[5] Portland Cement Association, "Cement & Concrete Basics FAQs," PCA, 2019, https://www.cement.org/cement-concrete/cement-and-concrete-basics-faqs.

[6] Colin R. Gagg, "Cement and Concrete as an Engineering Material: An Historic Appraisal and Case Study Analysis," *Engineering Failure Analysis* 40 (May 1, 2014): 114–40, https://doi.org/10.1016/j.engfailanal.2014.02.004.

[7] "Cement Draft," Science Based Targets, accessed February 4, 2022, https://sciencebasedtargets.org/sectors/cement.

[8] Timperley, Jocelyn, "Why Cement Emissions Matter for Climate Change," Carbon Brief, September 13, 2018, https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change.

[9] Timperley, Jocelyn.

Over the past two decades, there have been several attempts and initiatives to incentivize emission reduction strategies and reduce the carbon intensity of the industry; however, cement production remains a leading industrial emitter.[10] Notably, the Climate Action Reserve (Reserve) evaluated the potential for a blended cement protocol in 2008, though the effort was tabled as it was believed that a federal cap-and-trade program was imminent in the US.[11] However, Congress failed to enact a nationwide emission trading scheme, leaving open the opportunity for the voluntary carbon market to stimulate adoption of successful carbon reduction strategies in cement production.

There are numerous potential strategies to reduce emissions associated with cement manufacturing, including through energy efficiency improvements; fuel switching; carbon capture, utilization and storage (CCUS); and product replacement (i.e., reducing clinker-to-cement ratio).[12] This document will focus on the latter by evaluating the opportunity to displace conventional carbon-intensive OPC with new and emerging low carbon replacements called supplementary cementitious materials (SCMs). The purpose of this issue paper is to review the potential to reduce GHG emissions in the cement industry that would not have occurred otherwise by developing a Low Carbon Cement Production Protocol through the Reserve and generating voluntary offset credits, or Climate Reserve Tonnes (CRTs).

This issue paper begins with an overview of the various types of cement, along with cement production history and market trends in the United States and abroad. Next, it summarizes existing literature and market data. The following section provides an evaluation of additionality by outlining existing legislation and standards as well as describing how CRTs can help incentivize innovation and bring new SCMs to the market. The paper concludes with a review of existing methodologies and a discussion of proposed protocol composition.

2. Types of Cement & Concrete

At present, the construction industry utilizes numerous types of cement, with OPC being the most common and standard form. It is also the most carbon-intensive, producing just under one tonne of CO_2 per one tonne of OPC created.[13] OPC can be replaced with SCMs to form a lower carbon cement, ultimately reducing concrete-associated emissions. The following sections further

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[10] "Cement Sustainability Initiative (CSI)," World Business Council for Sustainable Development (WBCSD), accessed February 4, 2022, https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Cement-Sustainability-Initiative-CSI.

[11] Climate Action Reserve, "Issue Papers," Climate Action Reserve, accessed May 19, 2022, http://www.climateactionreserve.org/how/future-protocol-development/issue-papers/.

[12] Vass et al., "Cement."

[13] Portland Cement Association, "Carbon Footprint," n.d.

discuss the history, market, and manufacturing emissions associated with OPC as well as potential additive replacement materials to reduce GHG emissions.

2.1. Ordinary Portland Cement Manufacturing Process & Emissions

OPC, developed in the early 19th century, is a hydraulic cement comprised of mineral compounds containing calcium, silicon, iron, and aluminum. It is currently the most common type of cement utilized across the world because it is institutionalized in construction specifications, widely available, highly versatile, and economically attractive. However, OPC manufacturing requires high temperature processing and involves a chemical reaction that emits GHG emissions, making it an extremely energy- and carbon-intensive process. OPC makes up only a small portion of the concrete mix by mass (approximately 10%); however, it composes roughly 80% to 90% of concrete's total GHG emissions.[14]

OPC is manufactured by mixing calcium containing minerals, such as limestone, with silica alumina minerals such as sand, shale, or clay. This mixture is then formed into clinker by drying, grinding, and heating the raw materials in a rotary kiln. When the mixed raw materials are placed in the rotary kiln and subjected to extreme heat (nearly 2,700 degrees Fahrenheit), a chemical process occurs that transforms the calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and CO_2 gas, which is emitted into the atmosphere (Equation 1).[15] Next, the clinker is combined with gypsum and other various products and finally ground into OPC, which is then sold as a powder to make concrete (Figure 1).[16]

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Equation 1. Chemical reaction called calcination that occurs during clinker production and represents about half of the emissions associated with OPC production.

[14] Alex Johnson, "California Enacts Legislation to Slash Cement Emissions," NRDC, September 23, 2021, https://www.nrdc.org/experts/alex-jackson/california-enacts-legislation-slash-cement-emissions.
[15] Shakeb Afsah, "CDM Potential in the Cement Sector: The Challenge of Demonstrating Additionality," *Performeks LLC*, May 2004, 30.
[16] Portland Cement Association, "How Cement Is Made," Portland Cement Association, 2019, https://www.cement.org/cement-concrete/how-cement-is-made.

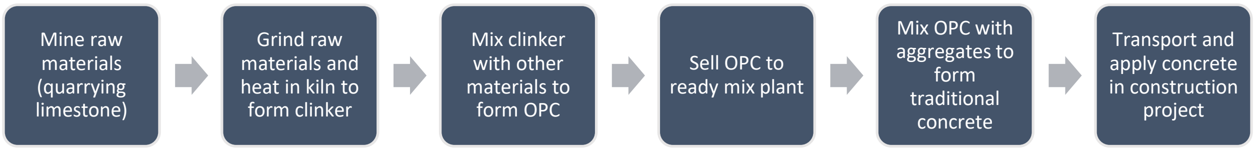

Figure 1. Overview of the typical manufacturing process for OPC and traditional concrete in the United States.

Due to the calcination process, the production of portland cement clinker is the most carbon-intensive component of the cement production process, representing over half of the production emissions.[17] The bulk of the remaining emissions are produced by fuel combustion for heating the kilns to high temperatures and for mining and transporting the materials (Figure 2).[18]

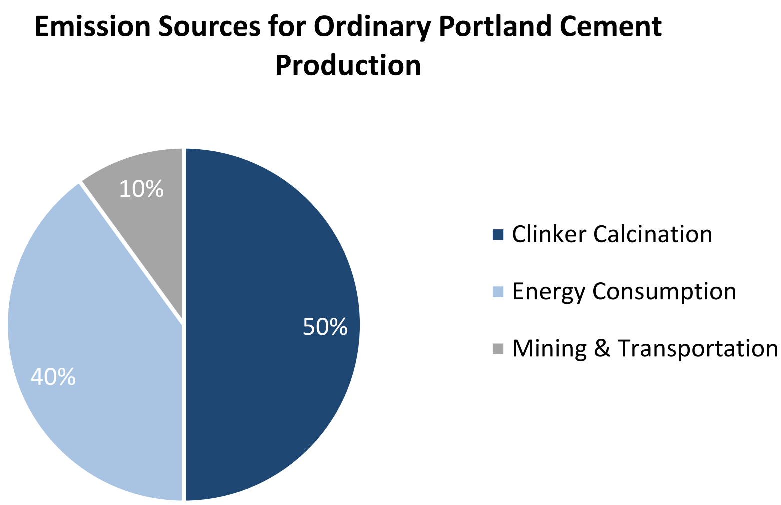

Figure 2. Emission sources from ordinary portland cement production.[19]

In the US, cement plants contributed to roughly 67,000,000 tonnes of carbon dioxide equivalent (CO_2e) in 2019.[20] The clinker-to-cement ratio, or the proportion of clinker integrated in each batch of cement, is a critical component in determining the emissions intensity of cement. ASTM International, formerly known as the American Society for Testing and Materials, establishes

[17] Lehne, Johanna and Preston, Felix, "Making Concrete Change: Innovation in Low-Carbon Cement and Concrete," Chatham House – International Affairs Think Tank, June 13, 2018, https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete.
[18] Timperley, Jocelyn, "Why Cement Emissions Matter for Climate Change."
[19] Timperley, Jocelyn.
[20] US Environmental Protection Agency, "U.S. Cement Industry Carbon Intensities (2019)," *US Environmental Protection Agency*, October 2021, 2.

procedures and standards for testing cements; to be ASTM certified as OPC, the product must include 90% to 95% clinker.[21]

As previously noted, there are a multitude of options to reduce emissions associated with cement production including upgrading to more energy efficient kiln equipment, transitioning to renewable fuel sources, implementing CCUS and reducing the amount of clinker used in cement (referred to as the clinker-to-cement ratio). The potential emission reduction impacts are greater for reducing the clinker-to-cement ratio and implementing CCUS compared to fuel switching or energy efficiency improvements.[22] Only about 20% of GHG emissions can be reduced by operational improvements.[23]

The cement industry has recently implemented technology improvements to reduce emissions; however, these emission reductions have been counterbalanced by an increasing clinker-to-cement ratio.[24] This proportion varies widely across the globe, although the International Energy Agency (IEA) estimates the 2020 average clinker-to-cement ratio to be 0.72.[25] As global decarbonization becomes increasingly urgent, the cement industry will be faced with a burgeoning need to further reduce the clinker-to-cement ratio by displacing OPC with a higher blend of new and existing SCMs.

2.2. SCM Concrete & Blended Cement Manufacturing Process & Emissions

The cement and concrete industries can abate emissions by displacing OPC and the associated clinker with additives referred to as SCMs. SCMs are byproducts of other industrial processes or natural materials that display cementitious and pozzolanic properties in concrete mixtures. Some SCMs can be used directly in cement or concrete manufacturing, and some require further processing before displaying required performance characteristics.[26] The two most well-known groups of SCMs used in cement and concrete production are fresh fly ash and ground granulated blast furnace slag (GGBFS), which are by-products of the declining coal and iron industry, respectively. In 2020, the US concrete industry utilized about 11,000,000 tonnes of fresh fly ash and approximately 2,600,000 tonnes of GGBFS. Silica fume, metakaolin, and natural pozzolans are also occasionally used as SCMs.

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[21] ASTM International, “Standard Specification for Portland Cement,” accessed February 4, 2022, https://doi.org/10.1520/C0150_C0150M-17.
[22] Vass et al., “Cement.”
[23] Czigler, Thomas et al., “Laying the Foundation for a Zero-Carbon Cement,” McKinsey & Company, May 14, 2020, https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement.
[24] Timperley, Jocelyn, “Why Cement Emissions Matter for Climate Change.”
[25] Vass et al., “Cement.”
[26] Slag Cement Association, “Slag Cement and Fly Ash,” 2013, https://www.slagcement.org/portals/11/Files/PDF/IS-11.pdf.

In the US, the addition of SCMs typically occurs at the ready mix concrete batch plant, where they are mixed with OPC and other materials to form SCM concrete. This allows concrete producers to customize the SCM replacement levels per batch of concrete. In other parts of the world, the replacement typically occurs at the cement production facility, where SCMs are mixed with OPC to develop blended cements.[27] For clarity, the term "blended cement" narrowly refers to a mixture of OPC and SCMs at a cement facility, which is later sold and mixed into concrete. "SCM concrete" refers to concrete that has one or more SCMs combined with OPC and other materials at a ready mix concrete batch plant.[28]

The production of blended cement or SCM concrete decreases the clinker-to-cement ratio, thus lowering the amount of CO_2 associated with processing each tonne of product. According to the National Ready Mixed Concrete Association (NRMCA), about 95% of ready mix plants use some amounts of SCMs with OPC to produce ready mixed concrete.[29] However, supply constraints materially limit the usage of SCMs. Further, SCMs can only be utilized up to a certain replacement rate, also known as the replacement ceiling, before negatively impacting the performance of concrete.[30]

Some players in the cement and concrete industry have expressed interest in achieving higher SCM replacement rates, though this solution is hindered by the diminishing supply of usable SCMs.[31] Fly ash and GGBFS are regionally limited and the other types of SCMs that are currently available are not able to be produced at the volumes needed to meet demand, thus they are not viable options to fill the growing SCM supply void.[32] The main SCM use limitations are depicted in Table 1.

[27] Thomas Van Dam and Federal Highway Administration, "Tech Brief Supplementary Cementitious Materials and Blended Cements to Improve Sustainability of Concrete Pavements" (Iowa State University, November 2013), https://intrans.iastate.edu/app/uploads/2018/12/SCM_tech_brief.pdf.

[28] The Loreti Group, "Greenhouse Gas Emission Reductions from Blended Cement Production Issues Paper" (California Climate Action Registry, December 19, 2008), https://www.climateactionreserve.org/wp-content/uploads/2009/03/future-protocol-development_blended-cement.pdf.

[29] National Ready Mixed Concrete Association, "Environmental Product Declaration - NRMCA Member Industry-Average EPD For Ready Mixed Concrete," January 3, 2022, https://www.nrmca.org/wp-content/uploads/2022/03/NRMCA_EPDV3-2_20220301.pdf.

[30] Barbara Pacewska and Iwona Wilińska, "Usage of Supplementary Cementitious Materials: Advantages and Limitations," *Journal of Thermal Analysis and Calorimetry* 142, no. 1 (October 1, 2020): 371–93, https://doi.org/10.1007/s10973-020-09907-1.

[31] Timperley, Jocelyn, "Why Cement Emissions Matter for Climate Change."

[32] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply," *Caltrans Office of Structural Materials*, 2020, 25.

Table 1. Limitations of supplementary cementitious materials in the United States.

Supplementary Cementitious Material	**Limitations**[33]
Fresh fly ash[34]	Insufficient and declining regional supply and varying quality
Slag/GGBFS[35]	Insufficient and declining regional supply and geographically limited
Silica Fume & Metakaolin[36]	High processing costs
Natural Pozzolans[37]	Geographically limited, varying quality, and limited market acceptance

3. Cement Production History & Market

The following sections review the current and historic state of the cement industry in the United States as well as internationally.

3.1. United States

The US is the fourth largest cement consumer in the world, with OPC being the most prevalent type of cement utilized.[38] The United States Geological Survey (USGS) publishes a monthly *Cement Mineral Industry Survey* that includes data on cement shipments and clinker production as well as an annual survey that summarizes domestic production and use. According to these USGS reports, there are 96 operating cement plants across 34 states and two additional plants in Puerto Rico. Roughly 45% of cement production and the majority of clinker production occurs within four top producing states: Texas, Missouri, California, and Florida. Three of these four top producers - Texas, California, and Florida - are also the top national consumers of cement.[39]

[33] US Department of Transportation Federal Highway Administration, National Concrete Pavement Technology Center, and Iowa State University Institute for Transportation, "Supplementary Cementitious Materials Best Practices Workshop," accessed April 21, 2022, https://intrans.iastate.edu/app/uploads/2018/03/SCMs_best_practices_workshop.pdf.
[34] Michael Thomas, "Optimizing the Use of Fly Ash in Concrete," *Portland Cement Association*, 2007, 24.
[35] Slag Cement Association, "Slag Cement and Fly Ash."
[36] Sidney M. Levy, "Section 5 - Calculations Relating to Concrete and Masonry," in *Construction Calculations Manual*, ed. Sidney M. Levy (Boston: Butterworth-Heinemann, 2012), 5, https://doi.org/10.1016/B978-0-12-382243-7.00005-X.
[37] Saamiya Seraj et al., "Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete" (The University of Texas at Austin, October 2014), https://library.ctr.utexas.edu/ctr-publications/0-6717-1.pdf.
[38] Timperley, Jocelyn, "Why Cement Emissions Matter for Climate Change."
[39] US Geological Survey, "Cement Mineral Commodity Summaries Annual Publication," January 2021, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf.

Over the past decade, domestic portland and masonry cement production has increased from an estimated 61,000,000 tonnes in 2010 to 87,000,000 tonnes in 2020 (Figure 3).[40] US exports are comparatively low (totaling around 1,000,000 tonnes of hydraulic cement and clinker), meaning that most of the cement and clinker are both produced and consumed domestically. The US is becoming increasingly reliant on imported cements reaching 18% of apparent consumption in 2021.[41] The COVID-19 pandemic caused some cement plant outages, although any negative effects did not appear to significantly impact the sector as the industry continues to grow, producing about 92,000,000 tonnes of portland and masonry cement in 2021.[42,43]

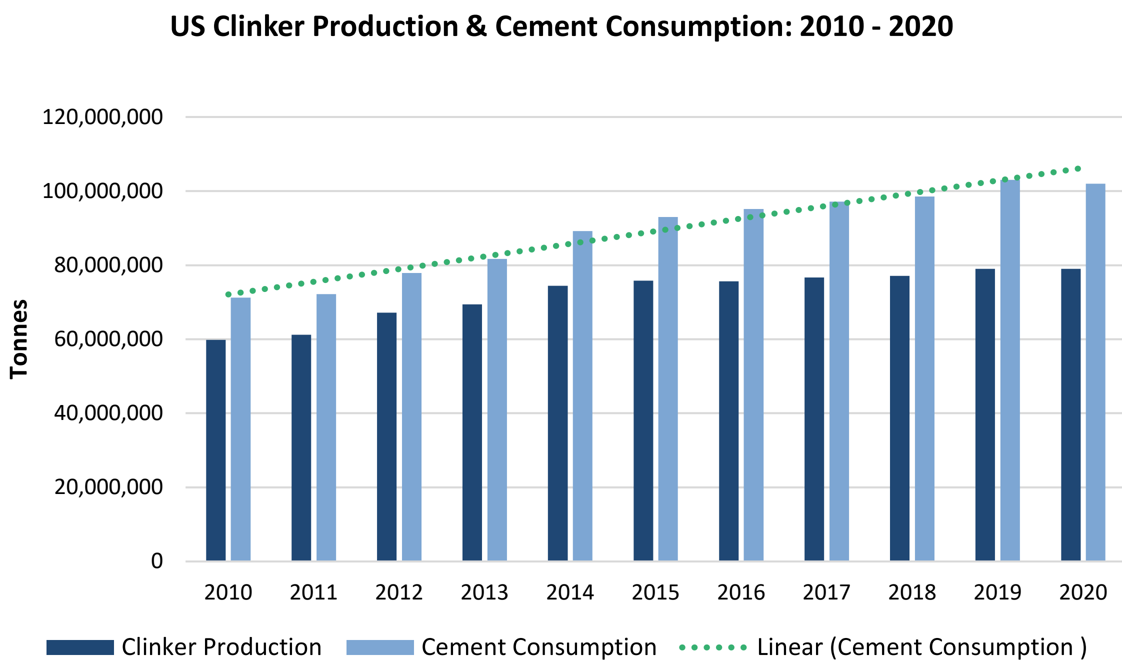

Figure 3. US clinker production and cement consumption: 2010 – 2020. Data courtesy of USGS.[44,45]

In 2020, blended cement shipments totaled nearly 3,000,000 tonnes. Most of these national shipments go to ready mix concrete producers (70% to 75%) with the remainder going to concrete product manufacturers (10%), contractors (8% to 10%), and other customers (5% to

[40] Masonry cement is used in masonry mortar, which binds bricks, stones, and blocks, and can also be used to create stucco. It consists of a mix of OPC and other materials.
[41] US Geological Survey, "Cement Mineral Commodity Summaries Annual Publication," January 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-cement.pdf.
[42] US Geological Survey, "Cement Mineral Commodity Summaries Annual Publication," January 2011, https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mcs-2011-cemen.pdf.
[43] US Geological Survey, "Cement Mineral Commodity Summaries Annual Publication," January 2021.
[44] US Geological Survey, "Cement Mineral Commodity Summaries Annual Publication," January 2011.
[45] US Geological Survey, "Cement Mineral Commodity Summaries Annual Publication," January 2021.

12%).[46] According to these data, blended cement accounts for approximately 3.3% of cement shipments in the US. However, as previously mentioned, the majority of SCMs in the US are added at the ready mix facility, so the market share of blended cement shipments does not reflect most of the SCM concrete produced in the country.

The NRMCA also collects and publishes state level data on total concrete produced.[47] The Portland Cement Association (PCA) is a domestic-based trade organization that supports policy, market research, and innovation throughout the cement value chain. In late 2021, the PCA released a *Roadmap to Carbon Neutrality*, which identifies increasing the acceptance and use of SCMs as a key strategy to reduce the clinker-to-cement ratio, although the amount that SCMs can contribute to reduced GHG emissions is dependent on their availability.[48]

3.2. International

Each year, an estimated 4 billion tonnes of cement are manufactured across the globe.[49] By 2030, cement production is expected to reach nearly 5 billion tonnes annually.[50] During recent years, infrastructure projects, primarily in China and India, have been the primary drivers of cement production (Table 2). In the coming decade, cement production in China is expected to level off; however, this decline will be offset by expected growth in infrastructure investments in other Asian countries, specifically India and Indonesia, as well as in Latin America.[51,52]

[46] US Geological Survey.
[47] "Surveys & Benchmarking," *NRMCA* (blog), accessed February 4, 2022, https://www.nrmca.org/association-resources/nrmca-surveys-benchmarking/.
[48] Portland Cement Association, "Roadmap to Carbon Neutrality - A More Sustainable World Is Shaped by Concrete," October 10, 2021, https://www.cement.org/docs/default-source/roadmap/pca-roadmap-to-carbon-neutrality_10_10_21_final.pdf.
[49] Lehne, Johanna and Preston, Felix, "Making Concrete Change."
[50] Timperley, Jocelyn, "Why Cement Emissions Matter for Climate Change."
[51] Vass et al., "Cement."
[52] Global Cement and Concrete Association, "Concrete Future The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete," October 12, 2021, https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf.

Table 2. Estimated world cement production in 2020. Data courtesy of USGS.[53]

Country	2020 Cement Production (tonnes)
World	4,100,000,000
China	2,200,000,000
India	340,000,000
Vietnam	96,000,000
US	90,000,000
Indonesia	73,000,000
Turkey	66,000,000
Iran	60,000,000
Brazil	57,000,000
Russia	56,000,000
Japan	53,000,000
Egypt	50,000,000
South Korea	50,000,000

There has been momentum on the international level to encourage collaboration and GHG emission reductions throughout the cement industry. The World Business Council for Sustainable Development (WBCSD), which emerged from the United Nations Conference on Environment and Development Earth Summit, joined with the top global cement producers in 1999 to assess and improve the industry's performance. In 2000, the WBCSD launched the Cement Sustainability Initiative (CSI), an international group of cement executives, to address and mitigate the cement sector's contributions to climate change.

The CSI developed a voluntary quantification protocol to account for GHG emissions in the cement sector.[54] The CSI also formed the Getting the Numbers Right database, an independently managed public database for energy and emissions information, to increase global transparency of energy and emissions data surrounding cement and clinker production.[55] The GNR database helped to develop baseline quantification approaches for projects with the Clean Development

[53] US Geological Survey, "Cement Mineral Commodity Summaries Annual Publication," January 2021.
[54] Cement Sustainability Initiative, "CO2 and Energy Accounting and Reporting Standard for the Cement Industry," May 2011, https://docs.wbcsd.org/2011/05/CSI-CO2-Protocol.pdf.
[55] Cement Sustainability Initiative, "Cement Industry Energy and CO2 Performance Getting the Numbers Right (GNR)," 2016, https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/.

Mechanism (CDM).[56] In 2009, the IEA and CSI developed a novel *Technology Roadmap* to reduce emissions in the cement industry, which has since been updated.[57]

In 2019, the Global Cement and Concrete Association (GCCA) formed a strategic partnership with WBCSD and thus took on managing the work of CSI. In the summer of 2021, the GCCA and the World Economic Forum launched the Concrete Action for Climate (CAC), which is an industry-led initiative to collaborate and coordinate strategies to reduce global GHG emissions and achieve a carbon neutral sector by mid-century.[58] The GCCA also launched a commitment to carbon neutrality in the sector by mid-century with the publication of *The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete.*[59]

Despite these global efforts, the cement industry remains a substantial industrial emitter and the clinker-to-cement ratio remains limited by SCM availability. The industry has made attempts to decarbonize over the past two decades, but there are still barriers faced by this hard-to-abate sector. The following sections discuss how the voluntary carbon market could help to overcome some of these challenges.

4. Evaluation of Supplementary Cementitious Materials

To better understand the use of SCMs as a replacement for OPC in blended cement and SCM concrete, this issue paper investigates the most well-known groups of SCMs. The following sections review the manufacturing process, state of the market and supply, standard replacement rates, and performance impacts of fresh fly ash, GGBFS, silica fume and metakaolin, and other natural pozzolans and alternative additives.

4.1. Fly Ash Description & Manufacturing Process

Fly ash, a pozzolanic material, is a coal combustion product, meaning that it is produced as a byproduct of coal-fired electrical generation.[60] At a power plant, coal is pulverized and blown into

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[56] Cement Sustainability Initiative.

[57] "Technology Roadmap," World business council for sustainable development, accessed July 9, 2018, https://www.wbcsd.org/Projects/Cement-Sustainability-Initiative/Resources/Technology-Roadmap-Low-Carbon-Transition-in-the-Cement-Industry.

[58] "Concrete's Path to Net-Zero Emissions in Focus as the World Economic Forum and the Global Cement and Concrete Association Join Forces to Deliver Concrete Actions for Climate," GCCA, accessed February 4, 2022, https://gccassociation.org/news/concretes-path-to-net-zero-emissions-in-focus-as-the-world-economic-forum-and-the-global-cement-and-concrete-association-join-forces-to-deliver-concrete-actions-for-climate/.

[59] "GCCS | Staging," GCCS | Staging, accessed February 4, 2022, https://gccassociation.org/concretefuture/.

[60] "Beneficial Use of Coal Combustion Products An American Recycling Success Story," accessed December 9, 2021, https://acaa-usa.org/wp-content/uploads/coal-combustion-products-use/ACAA-Brochure-Web.pdf.

a chamber where it ignites and creates a molten mineral residue, which is then cooled and hardened, creating ash. This fine powdery ash floats in flue gas and is then captured by emissions control equipment, resulting in fresh fly ash.

As a coal combustion residue, fly ash is considered a waste product, although the chemical and mechanical properties of fresh fly ash make it a valuable SCM to be mixed with OPC in the production of blended cement or SCM concrete.[61] Mainly made up of minerals containing silica, alumina, iron and calcium compounds, it has been utilized as an SCM in concrete for nearly a century. Fly ash has the potential to reduce the clinker-to-cement ratio resulting in decreased GHG emissions.[62]

4.1.1 Fly Ash Volumes & Availability in the United States

The national supply of fly ash is declining, and will continue to decline, due to coal power plant closures and fuel conversions at power plants. In 2020, U.S. coal production fell to its lowest level since 1965, consistent with coal capacity retirements depicted in Figure 4.[63] Coal plant closures are expected to reach an all-time high in 2028, in line with compliance deadlines set by the US Environmental Protection Agency (EPA) for regulating coal ash.[64]

[61] "Beneficial Use of Coal Combustion Products An American Recycling Success Story."
[62] American Coal Ash Association, "Fly Ash Facts for Highway Engineers," accessed February 1, 2022, https://www.fhwa.dot.gov/pavement/recycling/fafacts.pdf.
[63] Rosalyn Berry, "In 2020, U.S. Coal Production Fell to Its Lowest Level since 1965," EIA, July 14, 2021, https://www.eia.gov/todayinenergy/detail.php?id=48696.
[64] Darren Sweeney, Taylor Kuykendall, and Anna Duquiatan, "More than 23 GW of Coal Capacity to Retire in 2028 as Plant Closures Accelerate," accessed May 19, 2022, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/more-than-23-gw-of-coal-capacity-to-retire-in-2028-as-plant-closures-accelerate-68709205.

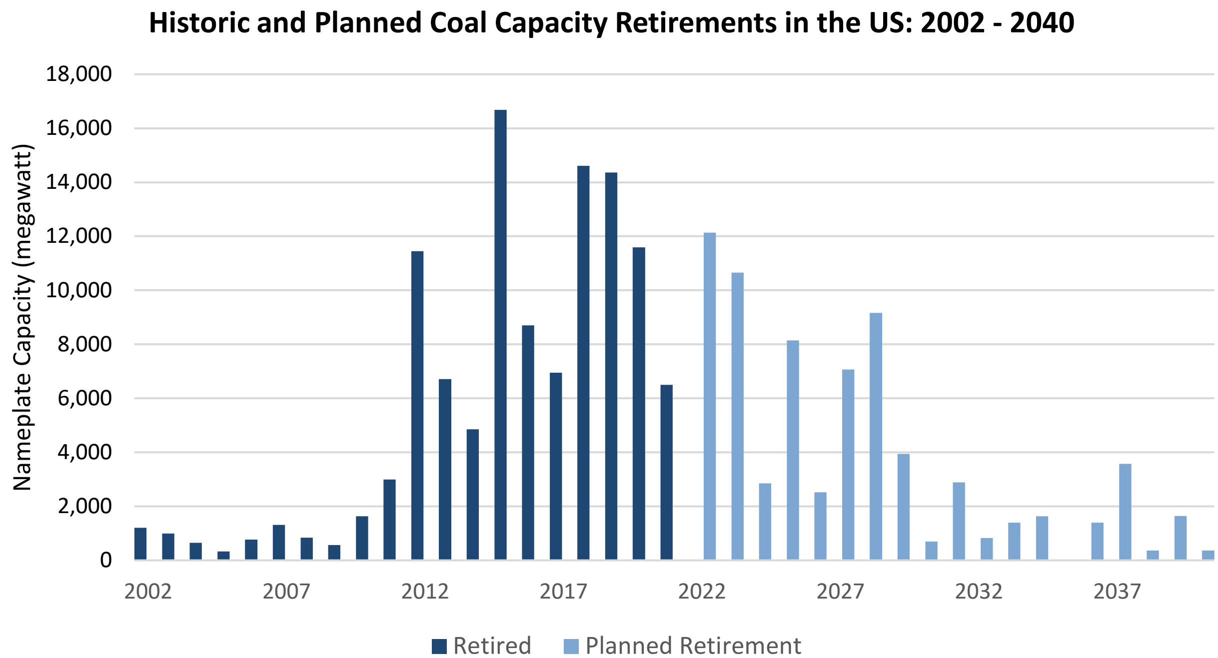

Figure 4. Historic and planned coal capacity retirements in the United States from 2002 to 2040. Data courtesy of the EIA.[65]

Coal-fired electricity generation has rapidly decreased over the past twenty years, declining from approximately 52% of utility-scale electricity generation in 2000 to roughly 19% in 2020, according to the U.S. Energy Information Administration (EIA).[66,67] Figure 5 reflects projected remaining coal capacity declining steadily through at least 2050.

[65] US Energy Information Administration, "Preliminary Monthly Electric Generator Inventory (Based on Form EIA-860M as a Supplement to Form EIA-860)," April 26, 2022, https://www.eia.gov/electricity/data/eia860m/index.php.

[66] US Energy Information Administration, "What Is U.S. Electricity Generation by Source?," EIA, November 2, 2021, https://www.eia.gov/tools/faqs/faq.php.

[67] "Electricity in the U.S. - U.S. Energy Information Administration (EIA)," accessed January 30, 2022, https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php.

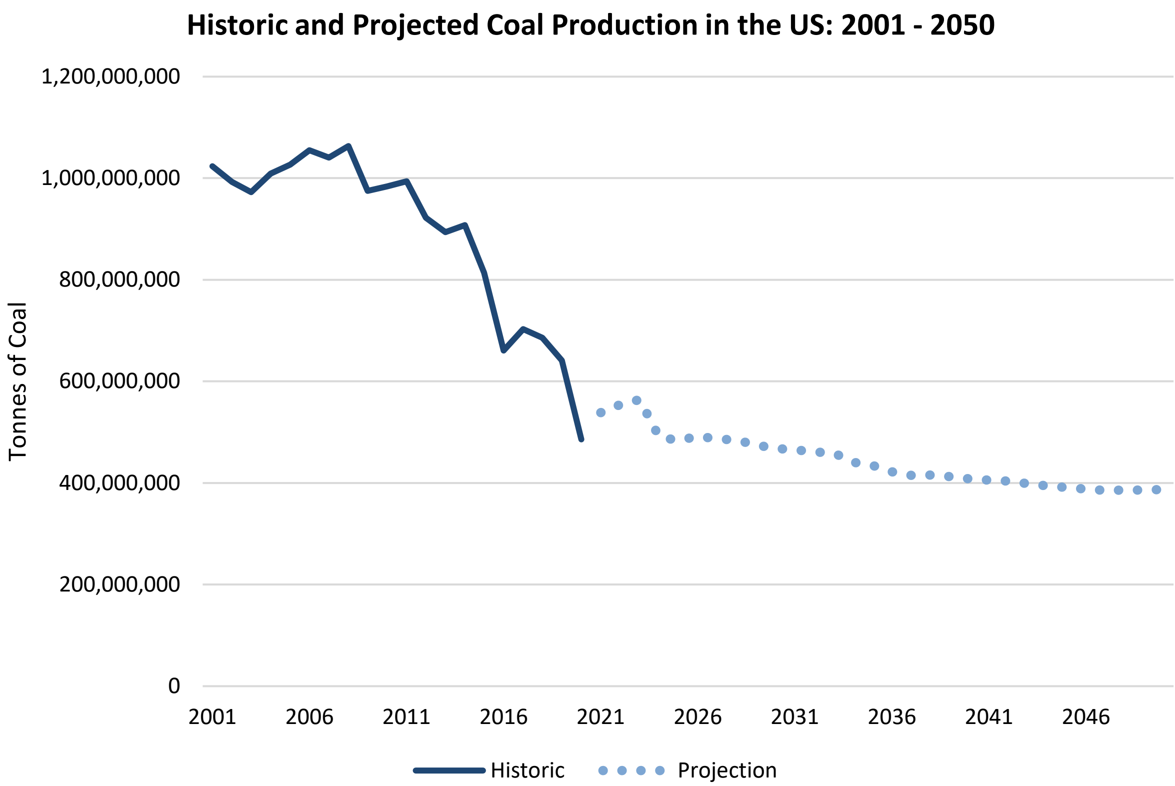

Figure 5. Historic and projected coal production in the United States from 2001 to 2050. Data courtesy of EIA.[68,69]

Fly ash supply has decreased in step with declining coal activities, from 61,000,000 tonnes in 2010 to roughly 26,000,000 tonnes in 2019 (representing a 57% drop) (Figure 6).[70] Yet cement consumption has continued to increase during this same period, further widening the gap between supply and demand for fly ash.[71] In response to fly ash shortages in California in 2016, the California Department of Transportation (Caltrans) observed that "with the increase in demand for fly ash and the projected growth over the coming decades, concerns have been

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[68] US Energy Information Administration, "Annual Energy Outlook 2022: Coal Production United States Total," 2022, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=95-AEO2022&region=0-0&cases=ref2022&start=2020&end=2050&f=A&linechart=~ref2022-d011222a.71-95-AEO2022&map=&ctype=linechart&sid=ref2022-d011222a.71-95-AEO2022&sourcekey=0.

[69] US Energy Information Administration, "Coal Data Browser," 2022, https://www.eia.gov/coal/data/browser/#/topic/33?agg=1,0&rank=g&geo=vvvvvvvvvvvvo&linechart=COAL.PRODUCTION.TOT-US-TOT.A&columnchart=COAL.PRODUCTION.TOT-US-TOT.A&map=COAL.PRODUCTION.TOT-US-TOT.A&freq=A&start=2008&end=2020&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin=COAL.PRODUCTION.TOT-US-TOT.A.

[70] Thomas H Adams, "Fly Ash Use in Concrete Increases Slightly As Overall Coal Ash Recycling Rate Declines," *American Coal Ash Association*, December 15, 2020, 5.

[71] American Coal Ash Association, "The Future of Fly Ash" (Iowa Better Concrete Conference, November 10, 2021), https://intrans.iastate.edu/app/uploads/sites/7/2021/11/A1B-Ward-Fly-Ash.pdf.

raised that demand will outpace available supply."[72] These shortages appear to persist over time and, as of 2018, the American Coal Ash Association (ACAA) estimated the gap between demand and supply of suitable fly ash to be roughly 25%.[73]

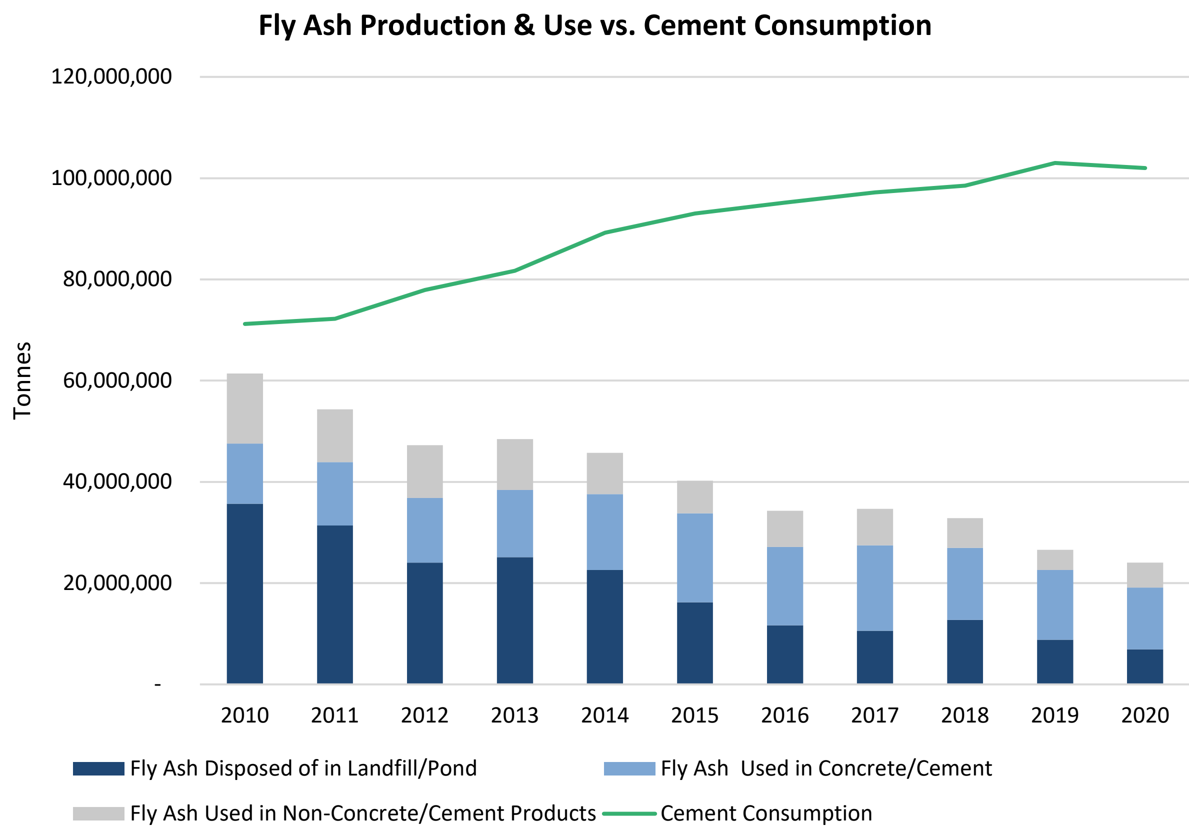

Figure 6. Fly ash production and use from 2010 to 2020. Data courtesy of the ACAA Production and Use Survey and USGS.

Fly ash usage in cement production is affected not only by coal production rates; important factors such as the fly ash quality, geographic location, and technological requirements also influence the ability to incorporate fly ash into cement production. The quality and properties of fly ash vary based on the type of coal burned and operations at the plant. Some types of coal produce fly ash that does not meet quality standards to be used as a replacement for OPC.[74] Under the Clean Air Act, coal-fired power plant operators are also required to implement pollution controls that impact the composition and quality of fly ash, making it unsuitable for

[72] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."
[73] CarbonCure, "The Future of Fly Ash in Concrete," CarbonCure Technologies Inc., December 1, 2020, https://www.carboncure.com/concrete-corner/the-future-of-fly-ash-in-concrete/.
[74] American Coal Ash Association, "The Future of Fly Ash."

concrete production.[75,76] In areas with regional supply shortages, the shipping costs associated with the distance and weight of the fly ash as well as the logistical hurdles involved in containing the fugitive dust often make fly ash economically unattractive for cement and concrete producers.[77]

Much of the fresh fly ash that is produced cannot be used because it is of low quality or too distant from cement plants. In 2019, only approximately half of the fly ash produced in the US could be beneficially utilized (e.g., cement and concrete production, asphalt filler, mining applications, etc.) with the remaining unsuitable fly ash being disposed of in landfills or ash ponds. Annually, there are millions of tonnes of fly ash produced that end up in the landfill instead of being beneficially used because they are either produced too far away from demand or their quality does not meet concrete grade specifications.[78]

Due to these limitations, the ACAA reports that multiple regions in the US are facing a significant supply shortage due to increasing demand and declining coal production.[79] For example, there is less coal produced in the western US compared to eastern states; this geographic variability contributes to significant regional shortages. California is especially impacted by the diminishing supply as it has high demand but is located far away from fly ash production.[80]

Currently, landfilled fly ash is an untapped resource that is hindered by significant and expensive processing and comingling challenges.[81,82] There are some early-stage projects in the US to harvest, or reclaim, disposed of fly ash, however the technology is prohibitively expensive and has not been deployed at scale.[83] The industry also lacks sufficient testing and research on the

[75] CarbonCure, "The Future of Fly Ash in Concrete."
[76] Texas Department of Transportation, "Fly Ash Supply Update", 2019 https://ftp.dot.state.tx.us/pub/txdot/mtd/ta/fly_ash_condensed.pdf
[77] Texas Department of Transportation, "Fly Ash Supply Update", 2019 https://ftp.dot.state.tx.us/pub/txdot/mtd/ta/fly_ash_condensed.pdf
[78] American Coal Ash Association, "The Future of Fly Ash."
[79] American Coal Ash Association.
[80] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."
[81] "Beneficial Use of Coal Combustion Products An American Recycling Success Story."
[82] Steven L Tritsch, Lawrence Sutter, and Ivan Diaz-Loya, "Use of Harvested Fly Ash in Highway Infrastructure," *Federal Highway Administration*, May 2021, 11.
[83] American Coal Ash Association, "The Future of Fly Ash."

performance of harvested fly ash, which faces additional hurdles due to varying quality, weathering, and contamination (landfills are mixed with other types of waste and minerals).[84]

There are also federal and state regulations that require the swift closure of ash disposal units, which limits the time to reclaim disposed fly ash. The cement industry will be required to make significant financial investments in technology and logistics to overcome the current supply constraints in the fly ash market.[85] To fill supply voids, ASTM International and other specification groups are beginning to consider expanding fly ash specifications to increase the use of bottom ash; however, these standards are not finalized and are not sufficient to fill regional supply gaps. Additionally, bottom ash supply will also be impacted by the declining coal industry.[86]

4.1.2. Fly Ash Limits & Considerations

The ASTM defines two classes of fly ash, class F (low-calcium content) and class C (high-calcium content), that have specific properties and specifications. The properties of fly ash are impacted by the type of coal burned as well as specific combustion conditions at the power plant.[87] The amount of fly ash utilized in cement varies due to the chemical properties, specification limits, and technical performance, although – when available, which it often is not – it typically ranges from 15% to 25% of the total mass of cementitious material.[88] Although uncommon, there are instances of using fly ash at higher levels, between 30% to 50%, for large structures that could benefit from temperature control during the curing process (e.g., dams and foundations).[89] In the US, the most common specifications for fly ash are under ASTM C618/American Association of State Highway and Transportation Officials (AASHTO) M 295 *Standard Specification for Coal Fly Ash and Raw or Calcinated Natural Pozzolan for Use in Concrete.*[90] ASTM is also in the process of developing standards for harvested fly ash, although the industry needs to better understand the processing and testing required to meet existing specifications.[91]

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[84] US Department of Transportation Federal Highway Administration, National Concrete Pavement Technology Center, and Iowa State University Institute for Transportation, "Supplementary Cementitious Materials Best Practices Workshop."
[85] Adams, "Fly Ash Use in Concrete Increases Slightly As Overall Coal Ash Recycling Rate Declines."
[86] American Coal Ash Association, "The Future of Fly Ash."
[87] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials," February 2016, https://www.fhwa.dot.gov/pavement/concrete/pubs/hif16001.pdf.
[88] Thomas, "Optimizing the Use of Fly Ash in Concrete."
[89] Thomas.
[90] "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," accessed February 3, 2022, https://www.astm.org/c0618-19.html.
[91] Tritsch, Sutter, and Diaz-Loya, "Use of Harvested Fly Ash in Highway Infrastructure."

Fly ash has the potential to improve performance of the final concrete product, however, fly ash typically negatively impacts the performance of the final product if blended above 25%.[92,93] Below 25% replacement, the possible performance improvements for SCM concrete with limited fly ash include improved workability, reduced bleeding, reduced permeability and chloride resistance, sulfate resistance, and reduced alkali-silica reaction (ASR).[94] These performance improvements extend the life of concrete. Above 25% replacement, there are various challenges to using fly ash in concrete production, including longer set times and extended strength development. The extended set time makes placement of the concrete more difficult and ultimately delays finishing, especially in cold weather.[95]

Similar to other SCMs, the properties of fly ash require specific storage requirements separate from OPC or other concrete ingredients. Fly ash must be stored in an individual, watertight, sealed silo which presents costly operational and infrastructure barriers.[96] The drivers and barriers to the use of fly ash are further summarized later in this paper in section 5. Evaluation of Additionality.

4.2. Slag Cement Description & Manufacturing Process

Slag cement, or GGBFS, is a hydraulic cement that uses GGBFS to replace a portion of OPC. GGBFS has been utilized in concrete production in the US for more than a century with even earlier applications in Europe.[97] GGBFS is recovered as a by-product during crude iron (also known as pig iron) production. Molten slag that has been diverted from an iron blast furnace is granulated and cooled forming a glassy state which is then ground into a fine cementitious material, or GGBFS.[98] According to the Slag Cement Association, slag cement has the potential to significantly reduce GHG emissions in the cement sector.[99]

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92 American Coal Ash Association, "Chapter 3 - Fly Ash in Portland Cement Concrete," US Department of Transportation Federal Highway Administration, June 13, 2006, https://www.fhwa.dot.gov/pavement/recycling/fach03.cfm.
93 Harun Mallisa and Gidion Turuallo, "The Maximum Percentage of Fly Ash to Replace Part of Original Portland Cement (OPC) in Producing High Strength Concrete" (AIP Conference Proceedings, Palembang, Indonesia, 2017), 030012, https://doi.org/10.1063/1.5011519.
94 "Materials Notebook Chapter 5 - Portland Cement Concrete," May 1997, https://www.fhwa.dot.gov/pavement/materials/matnote51.cfm.
95 Thomas, "Optimizing the Use of Fly Ash in Concrete."
96 American Coal Ash Association, "Chapter 3 - Fly Ash in Portland Cement Concrete."
97 Slag Cement Association, "Information Sheets 1: What Is Slag Cement," September 24, 2021, https://www.slagcement.org/Portals/11/xBlog/uploads/2021/9/24/SCA-Infosheets-1.pdf.
98 Slag Cement Association, "Slag Cement Benefits and Use in Concrete," Slag Cement Association, 2022, https://www.slagcement.org/resources/news/articleid/2/slag-cement-benefits-and-use-in-concrete.aspx.
99 Slag Cement Association, "Slag Cement and Fly Ash."

4.2.1. Slag Cement Market & Utilization

The USGS estimates that 3,200,000 tonnes of GGBFS were sold in the United States in 2019 and only 2,600,000 tonnes were sold in 2020.[100] In the US, GGBFS is in limited supply and is only available in select geographic areas. Slag is primarily available only east of the Rocky Mountains as most crude iron production plants are located in the central or eastern regions of the country.[101] In recent years, the domestic industry has experienced a trend of closing or idled blast furnaces, likely due to economics and industry transitions, causing a decrease in the national GGBFS supply. In 2019, there were only two active blast furnaces with granulated cooling in the United States.[102] The regional diminishing availability of GGBFS is also expected to worsen as the iron industry declines.[103]

It is often more cost effective to import slag; thus, most of the GGBFS consumed in the United States is imported from other countries.[104] Transportation costs for shipping slag to the west coast by rail are often prohibitively high, leaving west coast facilities to internationally import slag by ship (which itself generates significant GHG emissions).[105] Between 2016 and 2019, domestic consumers imported slag from Japan (29%), Brazil (18%), Canada (14%), Italy (12%), and various other nations (27%).[106] In the US, GGBFS production is limited and is not generated at sufficient volumes to fill the SCM supply void, even with imports.[107]

In some regions of the world, steel production is growing, including Japan and India, where GGBFS production is expected to increase to 22,000,000 tonnes and 16,000,000 tonnes, respectively. However, US producers are located too far away from these regions to economically seize the benefits of the growing regional supply.[108] There are also some regions where slag is underutilized and disposed of in landfills due to a lack of resource recovery regulation and

[100] US Geological Survey, "Iron and Steel Slag Statistics and Information," accessed April 22, 2022, https://www.usgs.gov/centers/national-minerals-information-center/iron-and-steel-slag-statistics-and-information.
[101] Slag Cement Association, "Slag Cement Questions," Slag Cement Association, 2022, https://www.slagcement.org/resources/faqs.aspx.
[102] US Geological Survey, "Iron and Steel Mineral Commodity Summaries," January 2020, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-iron-steel-slag.pdf.
[103] Global Cement and Concrete Association, "Concrete Future The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete."
[104] US Geological Survey, "Iron and Steel Mineral Commodity Summaries."
[105] The Loreti Group, "Greenhouse Gas Emission Reductions from Blended Cement Production Issues Paper."
[106] US Geological Survey, "Iron and Steel Mineral Commodity Summaries."
[107] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."
[108] CemWeek, "Japan and India to Drive Demand Growth in the GGBFS Market over the next 5 Years," CemWeek, February 17, 2021, https://www.cwgrp.com/cemweek-features/533810-japan-and-india-to-drive-demand-growth-in-the-ggbfs-market-over-the-next-5-years.

inadequate grinding facilities.[109] For example, China produces over 100,000,000 tonnes of steel slag annually, however only about 29.5% of the byproduct is utilized.[110] The industry has also been working to identify novel and previously unutilized sources of slag from the steel industry.[111]

The replacement rate of slag ranges from about 20% to 80% of cementitious material (by mass) according to the final application and property requirements.[112] The typical replacement range – where GGBFS is available in sufficient quantities – is around 25% to 50% for general applications.[113] For special mass concrete applications where internal temperature control is important, such as retaining walls and dams, slag cement replaces up to 80% of OPC, which is the highest potential replacement level.[114,115] Slag cement is more commonly used at higher replacement rates than other SCMs, such as fly ash, because it has more similar properties to OPC.[116]

4.2.2. Slag Cement Standards & Performance Impacts

Slag cement can be used as a separate component in concrete or as a mixture in blended cement. When it is used separately, ASTM C989-18 (AASHTO M 302-15) *Standard Specification for Slag Cement for Use in Concrete and Mortars* outlines the specifications and three grade classifications (i.e., Grade 80, Grade 100, and Grade 120) for slag cement based on strength.[117,118] For use in blended cement, slag is specified under C595, *Specification for Blended Hydraulic Cements* or ASTM C1157, *Standard Performance Specification for Blended Hydraulic Cement*.[119]

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109 Recycling Technology Worldwide, "Slag Recycling," Recycling Technology Worldwide, February 2020, https://www.recovery-worldwide.com/en/artikel/slag-recycling_3528047.html.
110 Jianlong Guo, Yanping Bao, and Min Wang, "Steel Slag in China: Treatment, Recycling, and Management," *Waste Management* 78 (August 1, 2018): 318–30, https://doi.org/10.1016/j.wasman.2018.04.045.
111 Global Cement Staff, "Betolar Plans to Replace 10% of Cement Used in Finland with Slag," Global Cement, March 25, 2022, https://www.globalcement.com/news/item/13877-betolar-plans-to-replace-10-of-cement-used-in-finland-with-slag.
112 Slag Cement Association, "Concrete Proportioning," 2013, https://www.slagcement.org/portals/11/Files/PDF/IS-02.pdf.
113 Slag Cement Association, "Slag Cement and Fly Ash."
114 US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
115 Slag Cement Association, "Slag Cement Questions."
116 Slag Cement Association, "Slag Cement and Fly Ash."
117 US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
118 Slag Cement Association, "Terminology and Specifications" (Slag Cement Association, 2013), https://www.slagcement.org/portals/11/Files/PDF/IS-12.pdf.
119 "Standard Specification for Blended Hydraulic Cements," accessed February 4, 2022, https://www.astm.org/c0595_c0595m-21.html.

If transportation emissions are disregarded or in the limited areas where there is sufficient local supply, slag cement has similar GHG reduction and performance benefits as other pozzolans.[120] Some of the potential benefits of slag cement include improved workability, enhanced finishability, reduced permeability, sulfate resistance, improved ASR mitigation, and a lighter color (which reduces thermal stress).[121,122] In fresh concrete, slag cement is easily consolidated, and it results in extended setting times as it has a slower reaction rate than OPC.[123] This slower setting time may cause durability and low early strength problems, which limit the type of applications that can use slag cement. Similar to other SMCs and OPC, GGBFS must be separately handled and stored in airtight silos.[124]

4.3. Silica Fume & Metakaolin

Silica fume, also known as microsilica or condensed silica fume, and metakaolin are grouped together in this section because they perform similarly and are both occasionally called for in high-performance and ultra-high-performance concretes (although, metakaolin is technically a natural pozzolan). Because of their high cost, silica fume and metakaolin are typically used primarily in applications that require low permeability and high strength, such as for dams and bridge-deck mixtures.

Silica fume, an extremely fine pozzolanic material, is derived from furnace smoke in the silicon metal production process.[125] Metakaolin is a highly reactive pozzolanic material made from the calcination of kaolin clays. To produce metakaolin, kaolin clays are run through a kiln and exposed to heat (1,300 to 1,600 degrees Fahrenheit) and then ground to form an extremely fine powder.[126] Due to this process, metakaolin production requires a high amount of energy consumption, which reduces the potential net environmental benefit.[127]

[120] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
[121] Slag Cement Association, "Slag Cement Benefits and Use in Concrete."
[122] Portland Cement Association, "Cement & Concrete Basics FAQs."
[123] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
[124] Slag Cement Association, "Producing and Placing Slag Cement Concrete" (Slag Cement Association, 2013), https://www.slagcement.org/portals/11/Files/PDF/IS-05.pdf.
[125] Silica Fume Association, "What Is Silica Fume?," Silica Fume Association, 2014, https://www.silicafume.org/general-silicafume.html.
[126] Claude Goguen, "A Closer Look: Fly Ash, Slag Cement & Metakaolin," National Precast Concrete Association, January 7, 2020, https://precast.org/2020/01/a-closer-look-fly-ash-slag-cement-metakaolin/.
[127] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."

Silica fume is not as widely used as fly ash or GGBFS due to its limited availability, challenging properties and high cost.[128] A literature review did not uncover any data sources for market volumes specific for silica fume. However, according to industry experts, it is consumed at very small volumes. Caltrans reports that the amount of usable silica fume is not sufficient to fill fly ash supply shortages and meet increasing demand.[129] The Silica Fume Association lists three silica fume producers in the United States, which are located in Pennsylvania and New York.[130] In the United States, kaolin clay deposits (for metakaolin) are typically found in the southeast, specifically throughout Georgia.[131] The USGS provides annual estimates for global and national kaolin clay production, which is primarily used for paper.[132]

Silica fume usually replaces 5% to 15% of the total mass of cementitious material.[133] When added to concrete, metakaolin typically makes up about 10% of the cement mass.[134] ASTM C1240/AASHTO M307 *Standard Specifications for Silica Fume Used in Cementitious Mixtures* includes specifications for the quality and use of silica fume in cement. Metakaolin is classified under AASHTO M 295 *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete* as a Class N natural pozzolan.[135]

Silica fume and metakaolin both have extremely fine particle sizes, which impact their properties and ultimately concrete performance. Both SCMs have the potential to increase water demand and decrease workability.[136,137] However, the small particle size allows for better packing density and ultimately increases strength and durability while decreasing permeability. Silica fume and metakaolin are typically used in applications that require low permeability and high strength,

[128] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
[129] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."
[130] Silica Fume Association, "Silica Fume Producers," Silica Fume Association, 2014, https://www.silicafume.org/general-producers.html.
[131] "Kaolin Capital of the World," Text.Article, NASA (NASA Earth Observatory, April 13, 2020), https://earthobservatory.nasa.gov/images/147689/kaolin-capital-of-the-world.
[132] U.S. Geological Survey, "Clays Mineral Commodity Summaries," January 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-clays.pdf.
[133] Levy, "Section 5 - Calculations Relating to Concrete and Masonry," 5.
[134] Goguen, "A Closer Look: Fly Ash, Slag Cement & Metakaolin."
[135] Thomas Van Dam and Federal Highway Administration, "Tech Brief Supplementary Cementitious Materials and Blended Cements to Improve Sustainability of Concrete Pavements."
[136] Goguen, "A Closer Look: Fly Ash, Slag Cement & Metakaolin."
[137] Thomas Van Dam and Federal Highway Administration, "Tech Brief Supplementary Cementitious Materials and Blended Cements to Improve Sustainability of Concrete Pavements."

such as for dams and bridge-deck mixtures. Silica fume costs more than OPC, making it less economical than fly ash or GGBFS (which are cost competitive with OPC).[138]

4.4. Natural Pozzolans & Alternative SCMs

The American Concrete Institute (ACI) defines natural pozzolans as "a siliceous or silico-aluminous material that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties."[139] Natural pozzolans are derived from mineral deposits such as volcanic ash. They have been used in construction for thousands of years. Most notably, the ancient Romans used natural pozzolans, derived from volcanic ash, to construct the Pantheon and Baths of Caracalla, which are both still standing today.[140] Alternative SCMs, such as rice husk ash or ground waste glass can be pozzolanic and are used in very limited markets.[141] Most natural pozzolans need a degree of processing (such as drying, calcining or grinding) before they exhibit the necessary properties to be used as a partial OPC replacement in concrete.

Natural pozzolans are not byproducts of other industrial processes; therefore, their supply is not linked to other industries. However, the availability of natural pozzolans is dependent on location and mineral deposits. The mineral deposits are located close to the surface and can be extracted with surface mining. There are volcanic mineral deposits located in some regions throughout the world, including in the western states, although only certain types of minerals display the pozzolanic properties required for concrete production.

Natural pozzolan producers have not been able to access these raw materials at a scale necessary to meet demand.[142] In addition to limited regional supply, there is a limited understanding by the cement industry of the performance and use of various natural pozzolans.[143] The composition of

[138] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
[139] American Concrete Institute, "Pozzolan," accessed December 9, 2021, https://www.concrete.org/topicsinconcrete/topicdetail/pozzolan#articles?search=pozzolan.
[140] Global Cement and Concrete Association, "Natural Pozzolans," GCCA, 2022, https://gccassociation.org/cement-and-concrete-innovation/clinker-substitutes/natural-pozzolans/.
[141] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
[142] Czigler, Thomas et al., "Laying the Foundation for a Zero-Carbon Cement."
[143] US Department of Transportation Federal Highway Administration, National Concrete Pavement Technology Center, and Iowa State University Institute for Transportation, "Supplementary Cementitious Materials Best Practices Workshop."

natural pozzolans also varies by region, rendering it impossible to guarantee uniform performance in concrete.[144]

Natural pozzolans act as a replacement for OPC in concrete production; however, the replacement rates are dependent on the type of pozzolan as well as the required characteristics of the final concrete product application. Similar to fly ash, natural pozzolan replacement levels are limited to 15% to 25% before having an impact on concrete performance.[145] ASTM C618 (AASHTO M295) *Standard Specification for Coal Fly Ash and Raw or Calcinated Natural Pozzolan for Use in Concrete* Class N provides specifications for natural pozzolans and ASTM C1709 *Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete* sets guidance for using alternative SCMs.[146,147]

The properties and performance impacts vary based on the type of SCM, level of processing, and replacement rate. However, natural pozzolans and alternative SCMs typically have the potential to improve concrete strength, durability, and workability as well as reduce ASR.[148]

5. Evaluation of Additionality

The protocol will only be applicable to project activities that bring innovative SCMs to market. The following section reviews the Reserve's additionality test, existing standards and legal requirements, and the drivers and barriers for using novel and OPC replacements in blended cement and SCM concrete.

5.1. Climate Action Reserve Additionality Test

According to the Reserve's Offset Program Manual, a standardized performance-based approach is utilized to determine if a project is additional, or beyond business as usual, and thus eligible to generate CRTs.[149] The first step in an additionality test is the legal requirement test: demonstrating that there are no laws or regulations that require the activity. If there is a law that

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[144] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."
[145] Saamiya Seraj et al., "Evaluating the Performance of Alternative Supplementary Cementing Material in Concrete."
[146] "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete."
[147] "Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete," accessed February 4, 2022, https://www.astm.org/c1709-18.html.
[148] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
[149] Climate Action Reserve, "Reserve Offset Program Manual" (March 12, 2021), https://www.climateactionreserve.org/wp-content/uploads/2021/03/Reserve_Offset_Program_Manual_March_2021.pdf.

requires adding new SCMs at a rate higher than stated in the methodology, projects in that region must be excluded from eligibility. The standardized test for this protocol will likely include the following criteria:

- *Legal Requirement Test:* The replacement of OPC with new SCMs is not mandated by law.
- *Technology Specific Threshold:* The SCMs are processed or treated to bring new and emerging SCMs to market.

As previously discussed, some SCMs are added to cement and concrete, depending on the type and availability of the additive; however, SCMs face supply constraints that impact their scalability. To avoid crediting for projects that would happen without the incentive of carbon offsets, we are proposing that this methodology include a technology specific threshold. This requirement will compel project proponents to process SCMs in a way that brings new and emerging SCMs to the US market (Table 3).

Table 3. Supplementary cementitious material proposed eligibility for US projects.

Supplementary Cementitious Material	US Project Eligibility
Fresh fly ash	Ineligible
Processed fly ash	Eligible
Traditional Slag/GGBFS	Ineligible
Processed Slag/GGBFS	Eligible
Silica Fume & Metakaolin	Ineligible
Natural Pozzolans/Alternative SCMs	Eligible

As fresh fly ash and traditional GGBFS are used at appreciable volumes, production of these SCMs would not constitute eligible projects under the protocol. Silica fume is costly and rarely used and metakaolin is also limited in use and requires high energy consumption for kiln heating, therefore these SCMs would not be eligible under the protocol. Processed fly ash, processed GGBFS, and natural pozzolans and other alternative SCMs were identified by our research as innovative categories of SCMs that have the potential to bolster the regional supply of SCMs. Through this protocol, carbon financing will incentivize the market to identify and recover these previously unused and novel SCM sources to help fill the nation's supply void.

5.2. Legal Requirements & Specifications

To generate CRTs, the project activity of replacing cement must not be required by any existing law or regulation in the region. The following sections further discuss the legal requirements and specifications in the United States and internationally.

5.2.1. Specifications in the United States

There are various standards that govern cement SCM content in the US. As previously discussed, there are a myriad of technical standards that exist for cement production to ensure consistency throughout the construction industry. Engineers and architects are generally most familiar with ASTM C150 *Standard Specification for Portland Cement,* and therefore it is the most frequently used standard for specifying performance levels in various building and design requirements.[150] These specifications impact the cement market because they have become the expectation throughout the national industry. In other words, many design requirements call for OPC rather than blended cement or SCM concrete. A ready mix facility that has limited space and infrastructure for their products (e.g., one silo), will often utilize their infrastructure to produce or use OPC because that is where the most market demand is.[151]

The AASHTO sets standards, guidelines, and test protocols for national highways and bridge construction. The AASHTO often adopts or references ASTM standards, although there can be slight differences between these two guidelines.[152] Each state has their own highway association which sets the specific standards for the type of cement used in state applications and public projects. Most state agencies limit the amount of SCMs allowed in construction projects.

ASTM International also classifies four types of blended cements with typical replacement limits based on the type of SCM (Table 4).[153] ASTM International includes specifications for Portland-Limestone Cement, which replaces OPC with limestone. American Concrete Institute (ACI) manuals are also commonly used throughout the industry, including by state highway agencies, as a guideline for concrete proportions.

[150] Thomas, Emily, "US Cement Standards: Accelerating the Green Transition," World Cement Association, April 16, 2020, https://www.worldcement.com/special-reports/16042020/us-cement-standards-accelerating-the-green-transition/.
[151] Thomas, Emily.
[152] *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 33rd ed. (American Association of State Highway and Transportation Officials, 2013), https://downloads.transportation.org/hm-33tableofcontents.pdf.
[153] "Standard Specification for Blended Hydraulic Cements."

Table 4. Four types of blended cement and the specified replacement rates as set by ASTM International.[154, 155]

Type	Typical SCM Replacement Rate
Type IP (Portland -Pozzolan Cement)	15% - 25%
Type IS (Portland-Slag Cement)	30% - 50%
Type IL (Portland-Limestone Cement)	10% - 15%
Type IT (Ternary Blended Cement)	15% - 30% slag and 10-20% pozzolan

5.2.2. Legal Requirements in the United States

Cement manufacturers must also comply with several environmental, health, and safety regulations. Under the US EPA Greenhouse Gas Reporting Program (GHGRP), cement plant operators within the United States and US territories are required to estimate and report their production process GHG emissions along with their cement and clinker production each year.[156] Moreover, the 2010 National Emissions Standards for Hazardous Air Pollutants, promulgated by US EPA under the federal Clean Air Act, implemented stationary source standards for hazardous air pollutants, which compelled numerous plants to install equipment to reduce air toxics emitted during kiln clinker production.[157] Cement producers and suppliers of their raw materials must also adhere to National Ambient Air Quality Standards, regulations for coal combustion residuals, and regulations around alternative fuels.[158, 159]

The US currently has no federal regulation, such as a cap-and-trade program or carbon tax, that requires GHG emission reductions in the cement industry or any national laws that require the production of blended cement or SCM concrete. It is unlikely that Congress will enact comprehensive legislation that requires industry-wide emission reductions or significant SCM use. However, if such an event were to occur, the Reserve could follow their stated guidelines

[154] US Department of Transportation Federal Highway Administration, "TechBrief Blended and Performance Cements" (Advanced Concrete Pavement Technology Implementation Team, January 2011), https://www.fhwa.dot.gov/pavement/concrete/pubs/hif11025/hif11025.pdf.
[155] Thomas Van Dam and Federal Highway Administration, "Tech Brief Supplementary Cementitious Materials and Blended Cements to Improve Sustainability of Concrete Pavements."
[156] US Environmental Protection Agency, "Cement Production Subpart H, Greenhouse Gas Reporting Program" (US Environmental Protection Agency, February 2018), https://www.epa.gov/sites/default/files/2018-02/documents/h_infosheet_2018_2.pdf.
[157] US Environmental Protection Agency, "National Emission Standards for Hazardous Air Pollutants Compliance Monitoring," Overviews and Factsheets, US Environmental Protection Agency, January 7, 2021, https://www.epa.gov/compliance/national-emission-standards-hazardous-air-pollutants-compliance-monitoring.
[158] Baer, Louis, "Energy & Environment Regulatory Priorities," Portland Cement Association, 2019, https://www.cement.org/issues-advocacy/regulatory-priorities/energy-environment-regulatory-priorities.
[159] OLEM US Environmental Protection Agency, "Disposal of Coal Combustion Residuals from Electric Utilities Rulemakings," Other Policies and Guidance, US EPA, 2014, https://www.epa.gov/coalash/coal-ash-rule.

and permit existing projects to finish respective crediting periods without the possibility of renewal.

Despite a lack of federal cement regulations to reduce GHG emissions, there has been momentum at the state level to decarbonize the cement sector; these efforts illustrate the increasing demand for reducing GHG emissions in the industry. In 2021, California enacted Senate Bill 596, a novel legislation that mandates the California Air Resources Board (CARB) to create and implement a plan to reach net-zero GHG emissions in the cement sector by at least 2045, including an interim goal of reducing emissions by at least 40% by mid-2035 (compared to 2019 levels).[160] California's cap-and-trade program also applies to cement plants, however cement imported into California is not covered by the program.[161]

In California, Caltrans already sets minimum amounts of required SCMs in state pavement and structure applications. These minimum requirements include 20% to 25% natural pozzolan or fly ash, 12% silica fume or metakaolin, or 50% GGBFS.[162] However, Caltrans has reported concerns around how the worsening shortage of suitable SCMs could impact current and future state construction projects.[163]

In 2021, New York legislators passed Senate Bill S542A, the Low Embodied Carbon Concrete Leadership Act, which directs the Office of General Services to set guidelines for utilizing low-carbon concrete in state projects.[164] In 2021, the New Jersey Legislature enacted a concrete mandate (S3091/A4933) that incentivizes lower carbon concrete for state projects by offering a tax credit for builders.[165] Colorado legislators also enacted a similar bill (HB21-1303) in 2021 that requires the office of the state architect and the department of transportation to create policies to reduce the global warming potential for specific public projects, including cement and concrete mixtures.[166] In the past, members of the Washington House of Representatives introduced, but failed to pass, the Buy Clean Buy Fair Washington Act (HB 2412-2017-18), which

[160] Johnson, "California Enacts Legislation to Slash Cement Emissions."
[161] "AB 32 Global Warming Solutions Act of 2006 | California Air Resources Board," accessed March 15, 2022, https://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006.
[162] Caltrans, "Revised Standards Specifications," October 15, 2021.
[163] Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."
[164] Addabbo Jr, Joseph et al., "NY State Senate Bill S542A," Pub. L. No. S542A (2021), https://www.nysenate.gov/legislation/bills/2021/s542/amendment/a.
[165] Addiego, Dawn Marie et al., Pub. L. No. S3091 ScaScaSa (3R), accessed January 27, 2022, https://www.njleg.state.nj.us/bill-search/2020/A4933.
[166] Chris Hansen, Barbara McLachlan, and Tracey Bernett, "Global Warming Potential For Public Project Materials," Pub. L. No. HB21-1303 (2021).

would have required state agencies to require Environmental Product Declarations (EPD) for construction projects.[167]

There are currently no regulations that require the use of the identified eligible SCMs in Table 3. If any state agencies specifically require the replacement of OPC with the novel SCMs identified in the protocol, projects that fall under the legislation in these regions may be ineligible for crediting.

5.2.3. International

Cement is widely utilized throughout the world, although there is a lack of a universal standard testing or classification system that is internationally applicable.[168] There is also no universal definition of blended cement; therefore, acquiring accurate data on widespread market penetration can be difficult. For these reasons, we believe an assessment of additionality at the national level will be appropriate in most instances.

Despite universal standards, nations across the globe are beginning to recognize the importance of decarbonizing the cement and concrete sectors. At the 2021 United Nations Climate Change Conference, COP26, five nations vowed to reach net zero in their concrete industry by 2050. The five countries, Canada, Germany, India, United Arab Emirates, and the United Kingdom, made commitments to support low-carbon cement markets.[169] Additionally, there are multiple country-level GHG reduction plans or national cap-and-trade schemes that involve the cement industry (Table 5).[170] The European Union's Emissions Trading System (EU ETS) implemented a cap-and-trade program for power plants and factories, including the cement sector.

[167] DeBolt, Doglio and Ormsby, Macri, "Creating the Buy Clean Washington Act," Pub. L. No. HB 2412-2017-18, accessed February 2, 2022, https://app.leg.wa.gov/billsummary?BillNumber=2412&Year=2017#documentSection.
[168] "Cement Types," accessed February 2, 2022, https://www.cement.org/cement-concrete/concrete-materials/cement-types.
[169] Henry Edwardes-Evans, "COP26: Five Developed Nations Commit to Support Low Carbon Steel, Cement Sectors," S&P Global Coal | Metals, November 9, 2021, https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/110921-cop26-five-developed-nations-commit-to-support-low-carbon-steel-cement-sectors.
[170] Vass et al., "Cement."

Table 5. International legislations that incentivize GHG emission reduction in the cement and concrete sectors.

Legislations	Description	Potential Protocol Expansion Implication
Australia Emissions Reduction Fund (ERF)	The ERF is a voluntary incentive program for organizations to generate Australian carbon credit units (ACCUs). The cement sector is eligible for this program; however, companies are not compelled to participate.[171]	This program is voluntary. Projects in Australia will likely still be deemed additional and thus eligible to generate CRTs with the protocol.
Canada's Output-Based Pricing System (OBPS)	In 2019, Canadian regulators implemented the OBPS, which set a requirement for provinces to set an industrial carbon pricing system or be subject to the federal OBPS federal carbon pricing system.[172]	The cement sector is included in the OBPS. Additional research is required to determine eligibility.
Chinese Emissions Trading Scheme	The People's Republic of China launched a national ETS in 2020 to limit emissions in coal and natural gas sectors. China plans to add additional sectors, including the cement industry, in 2022.[173]	If the cement sector is added to the ETS, projects in China may be deemed non-additional. Additional research is required to determine eligibility.
EU ETS	In 2021, the European Commission enacted the Fit-for-55 package, which includes removing the free allowances given to cement producers in the EU's ETS.[174]	Cement producers in the EU are subject to this legislation and will likely not be eligible to generate CRTs with this protocol.
India Perform, Achieve, and Trade (PAT)	The PAT scheme is a regulatory tool to incentivize energy efficiency improvements in emissions intensive industries, including the cement sector.[175]	The PAT incentivizes energy efficiency and would likely not exclude projects in India from generating voluntary carbon credits.
***Korea Emissions Trading Scheme* (K-ETS)**	The Republic of Korea launched the K-ETS in 2015, which includes the cement sector.[176]	Projects in this nation may be deemed non-additional, but additional research is required.

[171] "Emissions Reduction Fund," Government, Australian Government Business, November 18, 2021, https://business.gov.au/global/stenning-data/grants/emissions-reduction-fund.
[172] Environment and Climate Change Canada, "Output-Based Pricing System," program descriptions, Government of Canada, January 1, 2022, https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system.html.
[173] "China Plans to Add Aluminium, Cement to ETS next Year -Exchange," Carbon Pulse, December 6, 2021, https://carbon-pulse.com/145937/.
[174] "Foresight | The Revised EU ETS Can Accelerate the Decarbonisation of Cement," *Foresight* (blog), October 13, 2021, https://foresightdk.com/the-revised-eu-ets-can-accelerate-the-decarbonisation-of-cement/.
[175] International Energy Agency, "Perform, Achieve, Trade (PAT) Scheme – Policies," IEA, May 12, 2021, https://www.iea.org/policies/1780-perform-achieve-trade-pat-scheme.
[176] International Carbon Action Partnership, "Korea Emissions Trading Scheme," November 18, 2021, https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems%5B%5D=47.

5.3. SCM Usage Drivers and Barriers to Expansion

As discussed in section 4. Evaluation of Supplementary Cementitious Materials, the amount of SCMs used in cement have remained largely stagnant. While significant drivers exist to utilize a relatively moderate amount of SCMs, the industry faces challenges in overcoming supply constraints. In this section, we first discuss which drivers incentivize using SCMs as an OPC replacement. We then outline what barriers prevent an increase in replacement for existing and novel SCMs along with a summary of how carbon offsets would serve to remove these barriers.

5.3.1. Drivers for SCM Use

Different SCMs face different drivers for use; however, the main drivers are lower cost versus OPC, lower GHG emissions, and potential performance improvements. The cost of OPC compared to fly ash and GGBFS has varied over the years; however, the SCMs have historically been priced similarly or lower than OPC on a per-tonne basis (although, pricing varies by region and transportation modes and distance). These SCM cost savings are limited by potentially higher costs for transportation and the requirement to install new or specialized infrastructure. Alternatively, silica fume and metakaolin are priced higher than OPC, making them less financially attractive.

In addition to potentially lower costs, there are some programs and regulations that directly incentivize the use of SCMs. As previously discussed, Caltrans requires minimum SCM requirements for public projects. The EPA also has Comprehensive Procurement Guidelines (CPG) to encourage the use of recovered materials from municipal solid waste. The procurement guidelines direct agencies to permit the use of fly ash, GGBFS, and silica fume in cement and concrete projects; however, they are not required nor specifically recommended. The EPA's CPG guidelines state that SCM replacement rates are up to 20% to 30% for fly ash, 70% for GGBFS, and 5% to 10% for silica fume.[177] Builders may also be incentivized to use SCMs due to their lower GHG emissions; for example, the use of SCMs in any cement used in construction can lead to a higher score under the United States Green Building Council's voluntary Leadership in Energy and Environmental Design (LEED) certification.[178,179]

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[177] US Environmental Protection Agency, "Comprehensive Procurement Guidelines for Construction Products," Comprehensive Procurement Guidelines for Construction, US EPA, February 2016, https://www.epa.gov/smm/comprehensive-procurement-guidelines-construction-products.
[178] The Loreti Group, "Greenhouse Gas Emission Reductions from Blended Cement Production Issues Paper."
[179] US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."

5.3.2. Barriers to SCM Use

Increasing the use of SCMs faces several barriers that can be alleviated through carbon finance. These barriers can be broadly categorized into financial, market, institutional, and technical barriers, which will each be discussed in-turn in this section.

Cost challenges associated with SCMs are expected to be exacerbated in the future as the supply of today's most common SCMs decrease while the global demand for OPC grows.[180] Both fly ash and GGBFS are byproducts of industrial processes (coal-fired power generation and pig iron production, respectively) that are either phasing out of production or facing pressure to decarbonize and reduce waste themselves in some regions.[181] Nearly half of the fly ash that is available today in the US goes unused because it is produced too far from the replacement location, is not of appropriate quality (due to type of coal burned or emissions controls implemented), or it requires additional processing (which is either uneconomical or technically infeasible) to be suitable for beneficial use.[182,183] There is a limited and declining amount of GGBFS produced nationally, which makes it an infeasible alternative to fresh fly ash.[184]

Deposits of fly ash waste material can be harvested from landfills or disposal ponds, but this emerging procedure is technologically and geographically limited, costly, and requires additional processing.[185] Other potential replacement products, such as natural pozzolans, have the potential to meet demand but cannot be immediately used without additional processing and are currently not available at the scale needed to meet demand. In many cases, the technology exists to extract and re-process these alternative materials (e.g., disposed of fly ash and natural pozzolans) but they are not currently cost competitive with OPC. Because of this, increased replacement will not be possible in the future without innovation to increase the supply of SCMs. The GCCA reports that the industry will need a stream of research and development funding to secure a sustainable supply of SCMs, including mining natural pozzolans, to meet global demand.[186]

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180 Global Cement and Concrete Association, "Concrete Future The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete."
181 Czigler, Thomas et al., "Laying the Foundation for a Zero-Carbon Cement."
182 US Department of Transportation Federal Highway Administration, "Tech Brief Best Practices for Concrete Pavements Supplementary Cementitious Materials."
183 Tritsch, Sutter, and Diaz-Loya, "Use of Harvested Fly Ash in Highway Infrastructure."
184 Concrete Task Group of the Caltrans Rock Products Committee and Industry, "Fly Ash Current and Future Supply."
185 Tritsch, Sutter, and Diaz-Loya, "Use of Harvested Fly Ash in Highway Infrastructure."
186 "GCCAA-Concrete-Future-Roadmap-Document-AW.Pdf," accessed December 9, 2021, https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf.

Institutional barriers associated with market acceptance remain a key challenge despite the legacy use of SCMs throughout history. Since the 19th century, OPC has been the trusted standard product, with well-defined and understood performance and usability characteristics. Innovative products with a lower clinker-to-cement ratio (and thus higher SCM blend) are not as widely trusted and may be dismissed as a less safe or easy-to-use option.[187] Carbon finance can alleviate these barriers by creating an appealing financial incentive for buyers to give alternative products closer consideration. Moreover, CRTs can also help fund new standards and testing protocols, which are often time-consuming and costly to develop.

As noted earlier, on a per-tonne basis, some SCMs have historically been lower or equal in cost to OPC. However, concrete and cement producers that are not currently using SCMs face a "barrier to entry" cost to begin utilizing SCMs associated with additional storage equipment and potentially new processing technology. To use SCMs, a producer needs at least two silos to hold the material (one for OPC and one for the SCM). If they want to use more than one SCM, multiple silos are required as the cementitious material must be stored individually.[188] Carbon finance provides the opportunity to mitigate some of the higher upfront costs associated with incorporating more SCMs.

5.3.3. Summary of Additionality

Without a widescale market-based strategy or federal regulations, concrete and cement producers lack an incentive to invest in technology that enables innovative additives to enter the market. The drivers for using SCMs are currently counterbalanced and often outweighed by the supply gap and other financial and institutional barriers (Table 8). Carbon finances can provide funds that will help the industry to alleviate these obstacles that are preventing new SCMs from entering the market in the United States.

The revenue from CRTs can provide funds for research and development and help offset the costs related to transportation, storage, and processing (financial and technical barriers). This will allow more SCMs to enter the market and combat existing supply constraints (market barrier). When more SCMs are available in the market, the use of blended cement and SCM concrete may become more viable and economically attractive, which would thus encourage new standards to support the use of SCMs (institutional barrier) and further incentivize the development of novel processing technologies (technical barrier). Advancements in technology may enable new SCMs

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[187] The Loreti Group, "Greenhouse Gas Emission Reductions from Blended Cement Production Issues Paper."
[188] Thomas Van Dam and Federal Highway Administration, "Tech Brief Supplementary Cementitious Materials and Blended Cements to Improve Sustainability of Concrete Pavements."

to enter the market while overcoming limitations that prevent higher OPC replacement levels (technical and market barriers).

For example, fresh fly ash supply is currently insufficient and declining. Carbon finance could cover the cost barriers that currently prevent the technology advancements required to harvest, and process disposed of fly ash. This would allow innovative and currently unavailable SCMs (disposed of fly ash) to enter the market. This example can be applied to other existing and novel SCMs, including the extraction and processing of natural pozzolans.

Table 6. Summary of drivers and barriers to the use of supplementary cementitious materials in blended cement and SCM concrete in the United States.

Type of SCM	Drivers for Use	Barriers to Expansion
Fly Ash	• Performance improvements up to replacement ceiling (impermeability, durability, workability, etc.) • Cost is similar or less than OPC • Reduced GHG emissions	• Shortage due to declining regional supply • Variation in quality/composition • Industry standards favor OPC/limit replacement • Performance degradation beyond replacement ceiling (longer set time, early-age strength, etc.) • Infrastructure/storage costs • Lack of technology needed to harvest, and process disposed of fly ash • Lack of technology to mix beyond replacement ceiling
Slag Cement / GGBFS	• Performance improvements up to replacement ceiling (impermeability, workability, lighter color, etc.) • Cost is similar or less than OPC • Reduced GHG emissions	• Shortage due to low national volumes and declining regional supply • Transportation costs • Industry standards favor OPC/limit replacement • Perfomance degradation beyond replacement ceiling (longer set times, durability, etc.) • Infrastructure/storage costs • Lack of technology to mix beyond replacement ceiling
Silica Fume & Metakaolin	• Performance improvements up to replacement ceiling (density, strength, impermeability, etc.) • Reduced GHG emissions	• Cost of SCM is high • Limited regional availability • Low volumes available • Industry standards favor OPC/limit replacement • Performance degradation beyond replacement ceiling (workability, water demand, etc.) • Infrastructure/storage costs • Lack of technology to mix beyond replacement ceiling • High energy requirements for metakaolin kiln
Natural Pozzolans & Alternative SCMs	• Performance improvements up to replacement ceiling (strength) • Reduced GHG emissions	• Varying regional availability • Varying chemical composition • Extensive processing often required to utilize • Industry standards favor OPC/limit replacement • Performance degradation beyond replacement ceiling (early strength) • Infrastructure/storage costs • Widely accepted industry standards favor OPC • Lack of technology to beneficiate

6. GHG Emission Quantification Methodologies

The Reserve assessed the potential for a blended cement production protocol in 2008, including a detailed assessment by the Loreti Group outlining the state of blended cement in the US and the potential for protocol development. The lessons learned from past efforts will be incorporated in this protocol development process. The original issue paper identified multiple methodologies that can be utilized in developing this quantification. Since then, there have been other protocols that have been developed or updated. There are numerous existing methodologies that quantify manufacturing emissions from the cement sector. The most prevalent documents are:

- California Climate Action Registry: Cement Reporting Protocol[189]
- CDM ACM0005 Increasing blend in cement production[190]
- CDM AM0121 Emission Reduction from Partial Switching of Raw Materials and Increasing the Share of Additives in the Production of Blended Cement[191]
- CDM ACM0015 Emission Reductions from Raw Material Switch in Clinker Production[192]
- EPA GHGRP Subpart H Cement Production[193]
- Gold Standard Carbon Sequestration through Accelerated Carbonation of Concrete Aggregate[194]
- The Climate Trust Cool Climate Concrete (C^3) Emission Reduction Methodology[195]
- Verra's Verified Carbon Standard (VCS) VM0031 Methodology for Precast Concrete Production Using Sulphur Substitute[196]

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[189] California Climate Action Reserve, "CCAR Cement Protocol," CA Climate Registry, 2005, http://www.caclimateregistry.org/tools/protocols/industry-specific-protocols/cement/.
[190] "CDM: Increasing the Blend in Cement Production Version 7.1.0," accessed February 3, 2022, https://cdm.unfccc.int/methodologies/DB/1AG8O523O2UQD01BAID55YT2LZZ6R0.
[191] "CDM: Emission Reduction from Partial Switching of Raw Materials and Increasing the Share of Additives in the Production of Blended Cement --- Version 1.0," accessed February 4, 2022, https://cdm.unfccc.int/methodologies/DB/GRGJSJR47H63FGH9PLE3QOEQM0P4TO.
[192] "CDM: Emission Reductions from Raw Material Switch in Clinker Production --- Version 4.0," accessed February 3, 2022, https://cdm.unfccc.int/methodologies/DB/A8IL4OR2H1FWNDYYOJXCMCAA2JA9FV.
[193] "H_infosheet_2018_2.Pdf," accessed January 13, 2022, https://www.epa.gov/sites/default/files/2018-02/documents/h_infosheet_2018_2.pdf.
[194] Gold Standard, "Methodology: Carbon Sequestration through Accelerated Carbonation of Concrete Aggregate," March 7, 2022, https://www.goldstandard.org/our-work/innovations-consultations/methodology-carbon-sequestration-through-accelerated-carbonation.
[195] "Cool Climate Concrete - Offset Calculations," accessed February 3, 2022, http://www.coolclimateconcrete.com/offset-calculations/.
[196] "Verra - VM0031 Methodology for Precast Concrete Production Using Sulphur Substitute, v1.0," Verra, accessed February 3, 2022, https://verra.org/methodology/vm0031-methodology-for-precast-concrete-production-using-sulphur-substitute-v1-0/.

- Verra's VCS VM0043 Methodology for CO_2 Utilization in Concrete Production[197]
- WBCSD CO_2 and Energy Accounting and Reporting Standard for the Cement Industry[198]

Among these methodologies, the CDM methodologies, C^3 program, Gold Standard, and Verra's VCS methodologies are associated with the voluntary carbon market. The remaining methodologies are either for required or voluntary reporting. The CDM ACM0005 and C^3 are the only listed methodologies to have produced any voluntary credits at present. The CDM project search lists 17 registered projects under ACM0005 between 2006 to 2013. The C^3 program lists numerous project participants on their website, but the program has not been active since around 2013. The CDM's ACM0005, the Reserve's Cement Reporting Protocol, EPA GHGRP reporting calculations, the C^3 Emission Reduction Methodology, and the WBCSD reporting standard are most similar to the proposed protocol discussed in this issue paper. We will therefore include elements of these documents when relevant in the protocol design process.

7. Discussion of Protocol Composition

The components of the protocol will be further developed in the protocol development process; however, the key elements of project scope, quantification, leakage, ownership, permanence, and monitoring are introduced and discussed in this section.

7.1. Project Scope & Boundaries

The methodology will identify all sources, sinks, and reservoirs involved with SCM production. The project boundary for this methodology will likely include direct and indirect emissions from the SCM manufacturing plant. Direct emissions may include any on-site power generation, and indirect emissions may include power supplied from the grid. The boundary will also include transportation emissions associated with OPC and SCMs at the manufacturing site to point of sale.

Version 1 of this protocol will apply to projects in the United States. It is possible that this protocol may be updated in the future to expand the geographic boundary.

[197] "Methodology-for-CO2-Utilization-in-Concrete-Production-Carbon-Cure.Pdf," accessed February 7, 2022, https://verra.org/wp-content/uploads/2021/07/Methodology-for-CO2-Utilization-in-Concrete-Production-Carbon-Cure.pdf.
[198] Cement Sustainability Initiative, "CO2 and Energy Accounting and Reporting Standard for the Cement Industry."

7.2. Quantifying GHG Emission Reductions

The quantity of emission reductions will be determined by calculating the difference between the baseline emissions (i.e., business-as-usual OPC production) and the project emissions (i.e., SCM production) minus leakage emissions (Equation 2).

$$ER_y = BE_y - PE_y - LE_y$$

Equation 2. Quantification for net GHG emission reductions during reporting period.

Where:
ER_y = Net GHG emission reduction during reporting period (tCO_2e)
BE_y = Baseline emissions during reporting period (tCO_2e)
PE_y = Project emissions during the reporting period (tCO_2e)
LE_y = Leakage emissions during reporting period (tCO_2e)

Baseline emissions will likely be quantified using historic or regional data of OPC production along with published EPDs (Equation 3).[199] The baseline emissions will include OPC production emissions (from energy consumption and calcination) along with transportation emissions from the manufacturing site to point of sale.

$$BE_y = PR_b + TE_b$$

Equation 3. Quantification for baseline emissions.

Where:
BE_y = Baseline emissions during reporting period (tCO_2e)
PR_b = Production emissions for OPC during the reporting period (tCO_2e)
TE_b = Transport emissions for OPC during the reporting period (tCO_2e)

Project emissions may be calculated similar to baseline emissions, though it will include production and transport emissions associated with SCM processing (Equation 4). Production emissions will include energy consumption and transportation emissions will be from the manufacturing site to the point of sale.

$$PE_y = PR_y + TE_y$$

Equation 4. Quantification of project emissions during reporting period.

[199] Portland Cement Association, "Environmental Product Declaration Portland Cement," June 1, 2016, https://www.cement.org/docs/default-source/sustainabilty2/pca-portland-cement-epd-062716.pdf?sfvrsn=2.

Where:
PE_y = Project emissions during the reporting period (tCO_2e)
PR_y = Production emissions for SCM processing during the reporting period (tCO_2e)
TE_y = Transport emissions for SCM processing during reporting period (tCO_2e)

7.3. Leakage

When quantifying GHG emission reductions, it will be critical for the project proponent to ensure that the project activity is not increasing emissions elsewhere. Past methodology efforts have suggested that the increase of SCMs at one cement plant may increase the amount of traditional OPC at another facility.[200] However, this protocol differs from previous protocol efforts as the purpose is to increase the total amount of SCMs on the market.

As discussed in previous sections, the current supply of suitable SCMs is limited. This protocol will incentivize the use of additional SCMs and encourage new SCMs to enter the market, thus reducing current supply voids and not impacting current uses. Therefore, we do not expect this project activity to have significant leakage emissions.

7.4. Ownership

As the original issue paper states, there are potential complications with the ownership of CRTs as there are multiple parties that may wish to claim credit ownership, including the SCM manufacturer, the blended cement or SCM concrete producer, and the end user. However, the SCM manufacturer is the party taking action (processing SCMs) to reduce emissions and overcoming the discussed barriers to scaling; thus, we recommend that the SCM manufacturer have first ownership rights over any generated credits. The source of emission reductions also occurs at the SCM manufacturer as the alternative is OPC production. The SCM manufacturer is the recommended default owner, as SCM processing ultimately allows for new additives to enter the market. Ownership conflicts may also be overcome by a contractual agreement that clearly outlines the chain of ownership for emission reduction claims with the sale of SCMs.

7.5. Permanence

The avoided GHG emissions associated with producing blended cement and SCM concrete are permanent without the risk of reversal.

[200] The Loreti Group, "Greenhouse Gas Emission Reductions from Blended Cement Production Issues Paper."

7.6. Monitoring

The final Protocol will include a complete list of required monitoring and verification parameters based on the data required to quantify baseline and project emissions. These requirements are not finalized, but an example of these parameters may include:

- Quantity of SCMs produced
- Quantity of fuel combusted
- Quantity of electricity consumed
- Miles traveled and mode of transportation at OPC and SCM manufacturing site to point of sale
- Emissions factor of fuel consumed
- Emissions factor of the local electricity grid

8. Environmental and Social Impacts

A literature review has not identified any potential adverse social or environmental impacts related to SCM processing that have not already been discussed in Section 7.3 Leakage. However, it is possible that technology advancements to allow for new or increased SCM use could include chemical processing or surface mining for raw material extraction. Project proponents should monitor and mitigate any potential negative impacts, although affects will likely be minimal, especially compared to clinker production.

This methodology would incentivize the production and processing of SCMs that would likely end up at ready mix batch plants, which have been criticized due to localized air quality issues. The replacement of OPC with SCMs would likely not result in additional negative impacts, however project proponents should avoid processing SCMs in a way that releases volatile organic compounds at the ready mix plant and consider pollution controls when distributing processed SCMs.[201]

Low carbon cement and concrete have other positive co-benefits and are imperative tools for supporting safe and efficient urbanization and sustainable development efforts. Developing economies will require cement and concrete. Concrete and cement can help to achieve the United Nation’s Sustainable Development Goals. The production of clinker produces air pollutants, which will be reduced by the increased use of SCMs. Blended cement and SCM concrete will also likely result in reduced fossil fuel combustion as compared to clinker production.

[201] David Frederick, “Guide to Air Quality Permitting for Concrete Batch Plants” (The University of Texas at Austin Environmental Clinic School of Law, Fall 2018).

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