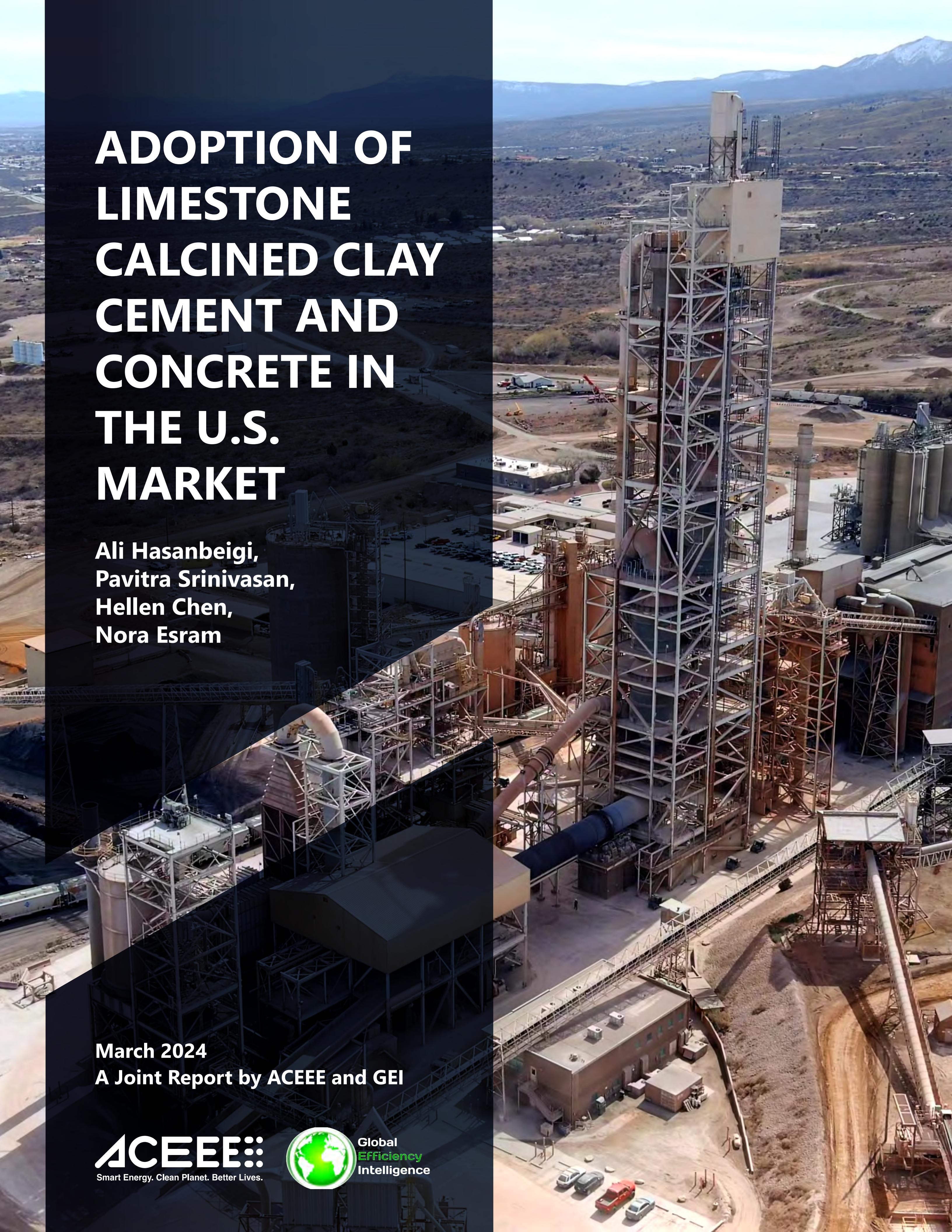

ADOPTION OF LIMESTONE CALCINED CLAY CEMENT AND CONCRETE IN THE U.S. MARKET

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Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

About GEI

Global Efficiency Intelligence, LLC is a U.S.-based research and consulting firm specializing in industrial decarbonization. The firm offers market-based solutions alongside comprehensive analyses of technology, systems, industry practices, business strategies, and policies relevant to the industrial sector. Utilizing systems thinking, integrative modeling, and data analytics, GEI transforms data into actionable insights and delivers science-based engineering solutions for global industrial decarbonization.

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Report cover photograph shows the Salt River Materials Group (SRMG) industrial facility in Clarkdale, AZ, owned by the Salt River Pima-Maricopa Indian Community. The company has produced cement, concrete, SCMs, and other raw materials such as natural pozzolans, including clays from U.S. sources, for more than seven decades. In the 1950s, one of the company's historical plants produced low-heat cement used to build the Glen Canyon Dam on the Colorado River.

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Glossary

Term	Definition
Blended cement	Cement that is made up of one or more supplementary cementitious materials (SCM) replacing a portion of clinker in portland cement. For example, limestone calcined clay cement is a blended cement.
Cement	Cement is the key binding agent in concrete. It is a combination of calcium, silicon, aluminum, iron, and other ingredients from materials including limestone, shells, and chalk or marl combined with shale, clay, slate, blast furnace slag, silica sand, and iron ore formed in a high-temperature process.
Concrete	A building product material resulting from a mix of cement, aggregate, water, and other additives.
Portland clinker	A dark gray nodular material made by heating ground limestone and clay at a temperature of about 1,400°C–1,500°C. The nodules are ground up to a fine powder to produce cement, with a small amount of gypsum added to control the setting properties.
Replacement	Occurs when new material(s) like SCMs replaces a portion of portland cement to form a blended cement. For example, limestone calcined clay cement is a replacement for portland cement.
Substitution	Adding SCMs to concrete instead of a portion of portland cement. In this scenario, the base product is still a portland (clinker-based) concrete.
Supplementary cementitious materials	Materials that contribute to the properties of hardened concrete through hydraulic or pozzolanic activity. Typical examples are fly ashes, slag, silica fume, and calcined clays. These can be used individually with portland or blended cement or in different combinations. Supplementary cementing materials are often added to concrete to make concrete mixtures more economical, reduce permeability, increase strength, or influence other concrete properties. (Abbreviated as SCM)

Abbreviations

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AML	Approved Materials List
ASTM	ASTM International (previously American Society for Testing and Materials)
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
DOT	Department of Transportation
EITE	Energy intensive, trade exposed
EPA	U.S. Environmental Protection Agency
EPD	Environmental product declaration
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GSA	Federal General Services Administration
IRA	Inflation Reduction Act
LCA	Lifecycle assessment
LEED	Leadership in Energy and Environmental Design
MnROAD	Minnesota Road Research Facility
Mt	Million metric tons
NGO	Non-governmental organization
NRMCA	National Ready Mix Concrete Association
PCA	Portland Cement Association
PLC	Portland limestone cement
SCM	Supplementary cementitious material
USGS	U.S. Geological Survey

Executive Summary

KEY FINDINGS

- Limestone calcined clay cement is a promising alternative to portland cement and one of the best solutions emerging for reducing carbon emissions from the cement industry. Under the current state of technology development, the carbon intensity of limestone calcined clay cement is 40% lower than portland cement. Calcined clays can be combined with limestone to produce blended cements or be used as a supplementary cementitious material in place of portland cement in concrete.
- Because 46% of cement purchased in the United States is used in public construction projects, federal, state, and local governments can achieve major emissions reductions by shifting their cement and concrete purchases to limestone calcined clay cement. We analyzed four market adoption scenarios and their associated emissions reduction potentials based on government-funded procurement. Shifting half of government purchases to limestone calcined clay cement could cut 7.3 million metric tons (Mt) CO_2 annually. This accounts for approximately 9% of the U.S. cement industry's total CO_2 emissions in 2021.
- If we take into account usage of limestone calcined clay cement in non-public construction projects, the potential impact of its adoption in the U.S. market more than doubles.
- Limestone calcined clay cement is cost effective, with production costs up to 25% lower than portland cement due to savings in energy and materials.
- Limestone calcined clay cement can help enable other decarbonization options for the cement sector. The lower temperatures (800°C) required in its production compared to portland cement (1,500°C) offer substantially improved process energy efficiency, which in turn opens the path for electrifying clay calciners. When combined with thermal energy storage options and renewable and other clean energy sources, this can lead to even greater emission reductions, approaching zero-emission scenarios.
- Governments, cement companies, concrete companies, and the non-governmental organization (NGO) community can help overcome technical, standards and codes, policy, market, and other barriers and increase the adoption of limestone calcined clay cement in the United States.

Cement manufacturing is one of the most energy- and carbon-intensive industries in the world, contributing around 7% of global carbon dioxide emissions (i.e., more than the food, beverage, paper, and non-ferrous metals industries combined). Cement is a key ingredient in concrete, the widely used building material, and its production will continue to rise globally in the coming years, especially in the global south. Decarbonizing the cement sector will therefore be essential to achieving the objectives of the Paris Climate Agreement, under which the world's countries committed to reduce their greenhouse gas emissions to net zero by 2050.

This report evaluates the potential of limestone calcined clay cement as a sustainable alternative to portland cement in the United States. We estimate the carbon reduction potential of different adoption rates (10%, 20%, 30%, and 50%) of limestone calcined clay cement by government and private cement users in the U.S. market in 2021, highlight the opportunity to realize these emissions reductions by shifting cement purchases for public construction projects, identify barriers, and offer recommendations to increase adoption.

Compared to portland cement, limestone calcined clay cement reduces emissions, performs as well, and is more cost effective (25%) due to savings in energy and materials

Cement is manufactured by heating limestone to a high temperature to create lime and carbon dioxide. The lime is further heated to produce clinker (an intermediate product), which is mixed with other materials to produce portland cement. Cement, a key binding agent, is mixed with aggregate and water to produce concrete, a widely used building material.

The CO_2 emissions from the cement industry can be reduced by (IEA and WBCSD 2018, Goldman et al. 2023):

- Improving energy efficiency.
- Improving material efficiency (e.g., by replacing portland clinker to produce blended cements, substituting portland cement with supplementary cementitious materials (SCMs) to produce concrete).
- Using alternative binding materials.
- Switching from traditional fuels to alternative fuels.
- Using decarbonized, alternative raw materials, and feedstocks.
- Using electrochemical production processes.
- Implementing carbon capture and storage.

Calcined clays represent a material efficiency approach that offers one of the best decarbonization opportunities for the sector, with substantial reductions in new carbon emissions possible, especially when combined with other decarbonization approaches like increased energy efficiency and electrification. Calcined clays can be combined with limestone and used to produce blended cements or be used as an SCM instead of portland cement in concrete. Calcined clays can use existing equipment, such as rotary kilns, reducing capital expenses, and they already enjoy acceptance in the standards community.

Limestone calcined clay cement is a low-carbon replacement for portland cement and can reduce CO_2 emissions by up to 40%, under the current state of technology development. It has undergone rigorous testing and been shown to perform as well as portland cement, while costing 25% less to produce due to savings in energy and material use. In addition, it offers adequate mechanical qualities (e.g., durability), making it appropriate for a variety of structural applications, including pavements, highways, residential and commercial buildings, and other infrastructure.

Limestone calcined clay cement is globally scalable. The use of limestone calcined clay cement has been studied in several countries around the world, including India, Brazil, Colombia, and Cameroon. This report discusses case studies from seven countries. Overall, limestone calcined clay cement is projected to account for more than one-quarter of cement use in the world by 2050 (IEA and WBCSD 2018). In the United States, the use of calcined clays has been very limited despite abundant clay deposits in many regions of the country, but there is growing interest.

U.S. CO_2 emissions can be reduced by 7.3 Mt annually by shifting half of federal, state, and local government procurement toward limestone calcined clay cement. This is equivalent to eliminating greenhouse gas emissions from driving 1.7 million gasoline-powered cars annually.

The United States is the fourth-largest producer of cement in the world, producing about 91 Mt of portland cement and masonry cement in 2023 (USGS 2024). Sales of cement in 2023 were around $16 billion (USGS 2024). At the state level, Texas, Missouri, California, and Florida have the highest cement production, in that order, and Texas, California, and Florida consume the most cement (USGS 2024).

Of the total amount (110Mt) of cement consumed (produced and imported) in the United States, 46% was used in public construction projects (PCA 2016), (i.e., about 47 Mt of cement). Three-quarters (75%) of public procurement is from state and local governments, with the remaining 25% from the federal government (Hasanbeigi and Khutal 2021). The U.S. cement industry emitted around 80 Mt of CO_2 in 2021 (calculated based on data from the U.S. Geological Survey (USGS) 2023 and U.S. Department of Energy (DOE) published in 2022).

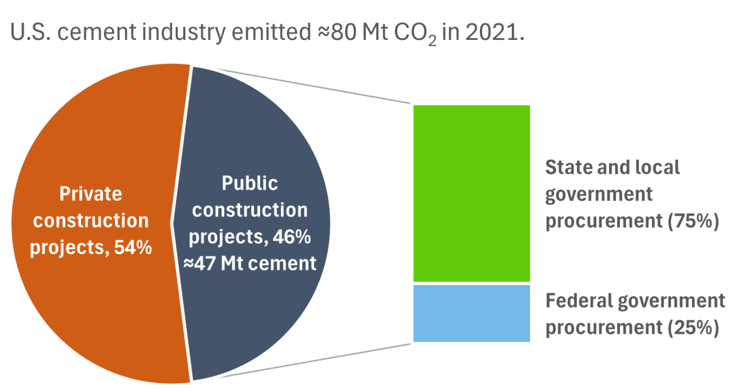


Figure ES-1. Share of cement consumption between private and public construction projects. Source: PCA 2016; USGS 2024, 2023; DOE 2022.

We conducted a scenario analysis using four scenarios to describe the adoption rate of limestone calcined clay cement by government and private cement users in the U.S. market in 2021—low (10% adoption across the market), medium (20%), high (30%), and transformative (50%)—and estimate the carbon reduction potential for each scenario. Even higher adoption rate scenarios may be possible based on market conditions over time. Based on this analysis, U.S. government (federal, state, and local) purchases of cement for construction can result in the emission reductions presented in Table ES-1.

Table ES-1. Summary of CO_2 reduction potential of limestone calcined clay cement used by government procurement in the United States

	Limestone calcined clay cement market adoption rate				
	None (Business as usual)	Low (10%)	Medium (20%)	High (30%)	Transformative (50%)
Annual CO_2 reduction potential from government procurement only (Mt CO_2)	0 Mt CO_2	1.5 Mt CO_2	2.9 Mt CO_2	4.4 Mt CO_2	7.3 Mt CO_2
CO_2 emissions of the U.S. cement industry in 2021 avoided from government procurement only (%)	0%	2%	4%	6%	9%
Equivalent to avoiding CO_2e emissions from number of gasoline-powered cars driven for one year (EPA 2024)	0	357,003	690,205	1,047,208	1,737,413

Assumptions:

1. **A 45% replacement rate of limestone calcined clay cement in portland cement, which leads to a 40% lower carbon intensity for limestone calcined clay cement compared to portland cement (business as usual).**
2. **Represents only government (federal, state, local)-procured concrete (46% of total procurement, the rest being mediated by the private sector).**
3. **Market adoption rates in each scenario of 10%, 20%, 30%, 50% create a range of emissions reductions based on level of adoption from low to transformative.**
4. **Estimates only emissions reductions due to material efficiency, not improvmements in energy efficiency or use of clean energy for electrical processes (e.g., grinders, calciners).**

Limestone calcined clay cement, a blended cement, produced by fossil fuel-based conventional calciners offers a 40% reduction in emissions over conventional portland cement. Electrification of the clay calciner, when powered by renewable energy, can help produce zero-emission calciner clay. If this zero-emission calcined clay is used in limestone calcined clay cement production, then the emissions reduction can be as high as 50%.

According to the U.S. Department of Energy (DOE) Pathways to Commercial Liftoff: Low-Carbon Cement report, electrification of precalciner/kiln technologies used in conventional portland cement production may achieve up to a 35% reduction in carbon emissions (Goldman et al. 2023). Thus, if clinker is also produced by an electrified precalciner/kiln using renewable or clean process heat and is coupled with zero-emission limestone calcined clay, then the limestone calcined clay blended cement would achieve about 70–75% emissions reduction compared to conventional portland cement.

Maturation of the calcined clay technology over time to include higher than 45% replacement rates in blended cement and concrete mix design efficiencies can further bring the total emissions reduction potential to 80% or higher in zero-emissions scenarios (compared to business as usual). Carbon capture, utilization, and storage (CCUS) can then be employed to reduce emissions further. These estimates underscore the importance of advancing research, development, demonstration, and commercial deployment of electrification technologies for the cement sector through the Inflation Reduction Act (IRA 2022), the Concrete and Asphalt Innovation Act (2023), and other policy initiatives.

Advancing such opportunities in the United States showcases American leadership in green manufacturing and demonstrates how innovation can transform this sector in other large cement-producing countries like China and India and globally.

Governments, cement companies, concrete companies, and the NGO community can help overcome barriers and increase adoption.

Barriers to adoption of calcined clays as an SCM in concrete and in a blended cement like limestone calcined clay cement include:

- **Technical barriers:** End users require their cement to maintain adequate mechanical properties and performance. While this has been demonstrated at lower replacement rates (40% and under), additional studies are required for replacement rates of limestone calcined clay cement in a portland blended cement higher than 50%. For example, additional studies and pilots are required to address reduced early age compressive and flexural strength of limestone calcined clay cements compared to portland cement in construction applications.
- **Codes and standards:** Limestone calcined clay is already covered in the ASTM International Standards C595, C595M, and C618. However, its application in the United States has been limited because of historical construction practices and insufficient production and suppliers in the country. In addition, existing industry standards and codes do not account for the higher replacement rate of calcined clays (40% currently allowed) or limestone (15% currently allowed) in limestone calcined clay cement (the blended cement) or calcined clays as an SCM in concrete (15% currently allowed).

- **Policy barriers:** There are no specific policies, regulations, or incentives for low-carbon cement alternatives, nor do all procurement policies consistently prioritize low-carbon options. This is partially due to the lack of awareness and understanding of the benefits of limestone calcined clay cement among policymakers and industry stakeholders.
- **Market barriers:** Barriers include, for example, the limited market penetration rate in replacing portland cement with limestone calcined clay cement, the fact that not all parts of the cement and concrete value chain are working to support adoption of limestone calcined clay cement, and the lack of training and practice guidelines for ready-mix operators (who represent the bulk of the market) to use limestone calcined clay cement. Generally, 70% to 75% of sales are made to ready-mixed concrete producers, 11% to other concrete product manufacturers, 8% to 10% to contractors, and 5% to 12% to other customer types.

To overcome barriers to the implementation of limestone calcined clay cement, we recommend the following:

- **Build supply by increasing financial support**. Producers should invest in cement production technology by upgrading or constructing new manufacturing facilities to raise manufacturing capacity. Government policies should create tax breaks such as accelerated depreciation for manufacturing equipment and a tax credit for material production.
- **Accelerate research, testing, and demonstration**. Industry, academia, and state governments should advance research and development; accelerate testing to improve performance, viability, and compatibility with concrete mix designs; conduct performance trials to boost product legitimacy and market confidence; support pilot and demonstration projects to test scenarios (e.g., in colder climates) and update state department of transportation (DOT) specifications; and share success stories through case studies to highlight viability and advantages.
- **Prioritize policy and standardization actions**. Governments should update or establish procurement and other policies to promote use, create markets, and set emissions-reduction goals. Governments and market entities should revisit existing cap and trade/invest policies to incorporate reduction potential from energy efficiency and electrification powered by clean energy from new technologies. The standards community should update standards and certification procedures to allow for more flexibility in limestone calcined clay cement replacement levels, performance requirements, and SCM substitution rates in concrete. Industry and the codes community should promote the use of limestone calcined clay cement in building codes and state DOT material specification lists.
- **Educate the market and policymakers**. Industry can offer technical assistance, training, and resources to customers. It can work with NGOs to educate end-users of cement, such as architects, engineers, developers, and public building owners, about limestone calcined clay cement and its environmental and climate advantages.

- **Value collaboration and integration.** To enable wider adoption, stakeholders should create partnerships with suppliers and contractors and create dependable supply chains and product availability at the right cost, promoting the use of calcined clays in construction projects. Industry and the architect and engineering communities can collaborate with governmental organizations to create policies that encourage use of calcined clays in construction, comment on proposed regulations, and leverage available technical resources. Governments can cooperate with industry stakeholders to promote calcined clays and aggregate demand.
- **Work with local communities.** NGOs can spread awareness of air quality and public health benefits.

Introduction

Cement production is among the most carbon- and energy-intensive industrial sectors in the world, accounting for roughly 7% of the world's total carbon dioxide (CO_2) emissions (Hasanbeigi 2021). The cement sector is the third-largest industrial emitter globally, after iron and steel and chemicals, but it is the industrial sector with the highest non-combustion process emissions, far more than all other industries (Rissman 2024). In 2023, the United States was the fourth-largest producer of cement globally, at 91 million metric tons (Mt), while global cement production as a whole was about 4,100 Mt (USGS 2024). The actual consumption of cement in the United States is even greater than domestic production, due to cement imports (about 27 Mt) from other countries (USGS 2024). Cement production has been steadily increasing globally over the past few decades and is projected to continue growing, according to the International Energy Agency (IEA and WBCSD 2018). As a result, decarbonizing the cement industry will be crucial to meeting the goals of the Paris Climate Agreement.

Cement manufacturing typically consists of three main steps:

(1) Raw materials and solid fuels are pre-processed using techniques like grinding, crushing, and drying.

(2) Raw materials are then heated to temperatures near 1000°C, leading to the decomposition of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and carbon dioxide (CO_2). The calcium oxide is subsequently heated to temperatures around 1500°C to form “clinker,” an intermediate product critical for early strength. Supplementary cementitious materials (SCM) are then added (MIT CSHub 2013).

(3) Clinker is then ground with gypsum and other additives in a mill to produce cement.

Cement is mixed with water, aggregate, and other additives as needed to form concrete, a widely used building and civil construction material. Cement is the key binding ingredient in concrete, representing about 15% of the mix.

Producing cement is a carbon-intensive process and is responsible for the bulk of the CO_2 emissions associated with concrete, so reducing emissions from cement is key to overall emissions reductions across the cement and concrete industries.

This report introduces the current state of the U.S. cement industry, including production, consumption, and CO_2 emissions, and analyzes the potential for using SCMs to reduce emissions, and explores the favorable properties of limestone calcined clay in cement or concrete.

It should be noted that SCMs can be added during both cement production and concrete production. When we suggest or assume higher use of SCMs, this increase can be at either cement plants or concrete plants in the United States. We can replace portland cement with SCMs to make a blended cement (meaning less portland cement, and thus less clinker, is produced or used). This can help to significantly reduce energy intensity per metric ton of cement produced and reduce the energy and carbon footprint of the final product. We can also substitute SCMs for portland cement in concrete, which reduces the energy and carbon footprint of the final product.

The subsequent sections of this report discuss the current status of limestone calcined clay cement in the United States and international case studies on limestone calcined clay cement. We briefly describe experiences with its use and evidence for its effectiveness in reducing CO_2 emissions while maintaining quality and improving durability.

In this study, we analyzed cement consumption and the potential emissions-reducing impact of limestone calcined clay cement in each state for all 50 states. The analysis is based on cement consumption and emissions data from U.S. states in 2021—the most recent year for which there is complete data available for all states at the time of this analysis. The analysis shows the potential CO_2 emissions reductions possible from the adoption of limestone calcined clay cement in the United States.

Moreover, there are other benefits of U.S. adoption of limestone calcined clay cement, including greater energy efficiency due to lower calcination temperatures and lower heat requirements. These changes allow cement production to use thermal storage or electrification for certain elements of process heat. In this report we present a business case for manufacturers and discuss community benefits from the reduction of CO_2 emissions.

Realizing all of these benefits will require stakeholders to address technical, codes and standards, policy, customer solution, and market acceptance barriers to adoption and implementation. This report concludes with policy recommendations and an action plan to overcome these barriers and to promote the adoption of limestone calcined clay cement in the United States.

Cement Production and Consumption in the United States

The United States produced around 91 Mt of portland cement and masonry cement in 2023 and is the fourth-largest producer of cement in the world (USGS 2024). Cement was produced at 93 plants in 34 states in 2021. Of those, 86 plants employed the dry kiln process, and seven used the wet or semi-wet kiln process (USGS 2023).

Wet kilns account for only 2% of total U.S. cement production. They are an older technology that combines raw materials in a water slurry; they use 33% more energy than dry process kilns—a newer, more-energy-efficient technology that does not use water to combine raw materials in the kiln (EPA 2010).

Sales of cement in 2023 were around $16 billion (USGS 2024). Texas, Missouri, California, and Florida have the largest cement production, in that order, with Texas, California, and Florida having the largest cement consumption, in that order (USGS 2024). Total cement shipments to final customers in the United States were 110 Mt in 2023, with the shortfall covered by imports (USGS 2024). Generally, 70% to 75% of sales are to ready-mix concrete producers, 11% to other concrete product manufacturers, 8% to 10% to contractors, and 5% to 12% to other customer types.

Of the total amount (110 Mt) of U.S. cement consumption, 46% was used in public construction projects (PCA 2016) (about 47 Mt of cement). It should be noted that in the majority of cases, the government and its contractors do not purchase cement (the key binding element in concrete), but instead purchase concrete (mainly ready-mix concrete), which is the final building material used in construction projects. The values shown in this report focus on the cement used in concrete that is used in construction projects because cement is the largest source of embodied carbon emissions in concrete and opportunities for reducing emissions lie primarily in modifying the constitution of cement (to create blended cements) and concrete (by adding SCMs).

We calculated the share of cement used in public construction (46%) compared to total U.S. cement use (PCA 2016) and used that as a proxy for estimating the cement used for public construction in each state. Around 25% of the total cement and concrete procured by governments in the United States is through the use of federal funds, with the remaining 75% from the use of state and local government-owned funds (Hasanbeigi and Khutal 2021), as illustrated in figure 1.

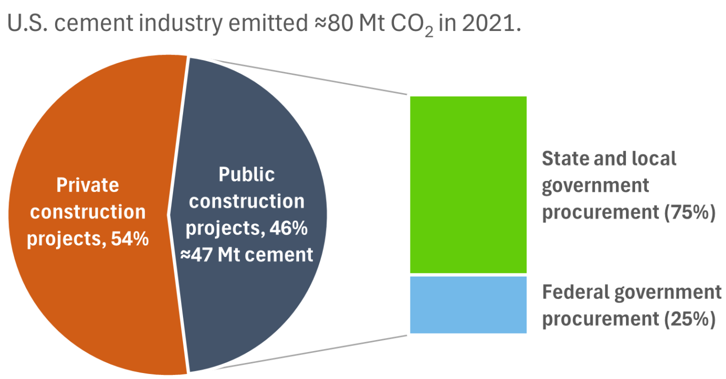


Figure 1. Share of cement consumption between private and public construction projects. Source: PCA 2016; Hasanbeigi and Khutal 2021; USGS 2024, 2023; DOE 2022.

Figure 2 shows total cement consumption for public and private construction in all 50 U.S. states. Among these states, Texas accounts for the highest cement consumption, followed by California and Florida. We used the general 25:75 ratio to estimate the government procurement of cement using federal funds and state and local government funds within each state (figure 2).

Since individual state data on cement used in public construction or levels of federal (military) funding by state either do not exist or are not publicly available consistently for all 50 states, this analysis uses harmonized assumptions across all states and relies on available federal level data and the use of a proxy.

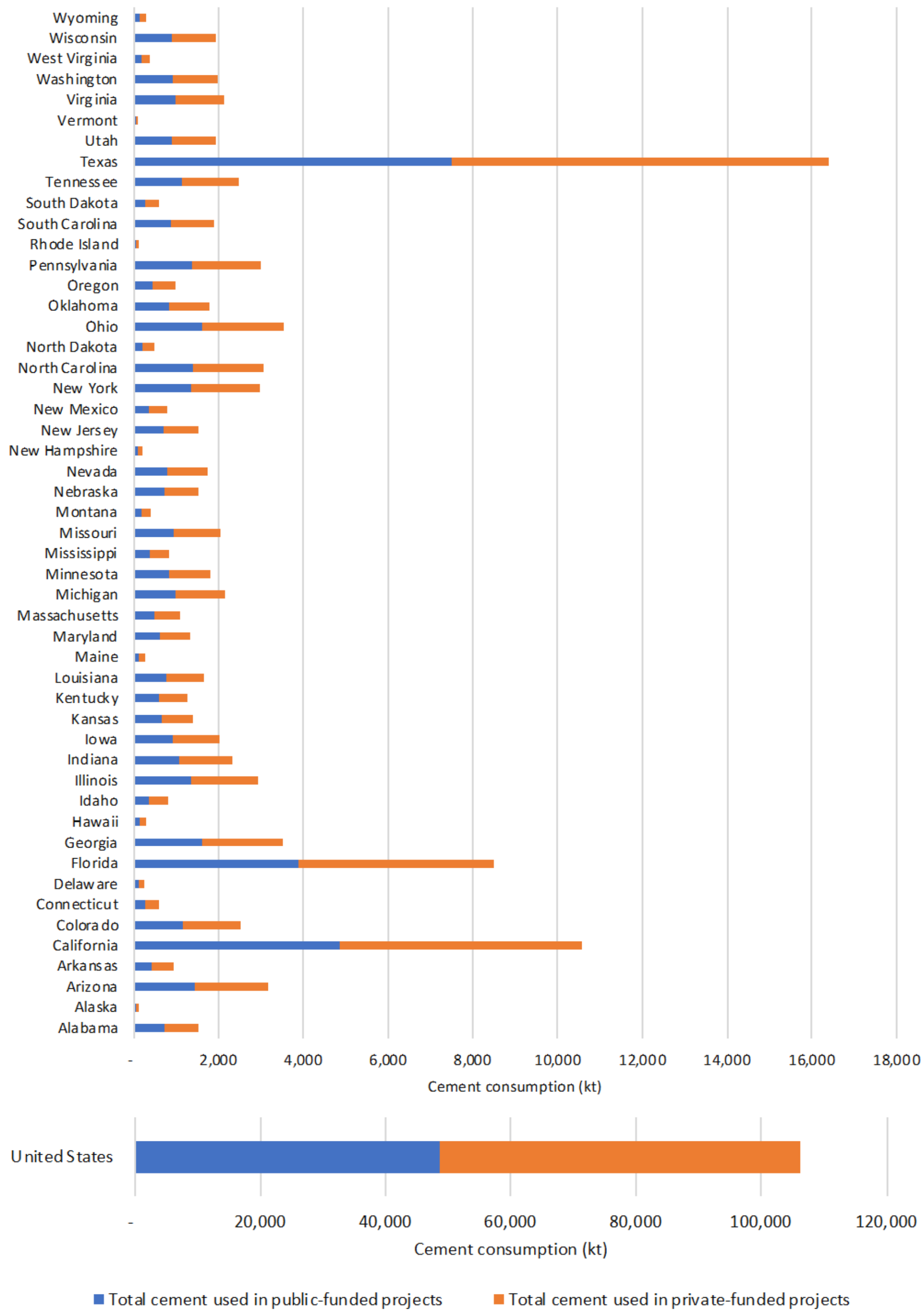


Figure 2. Total cement consumption for public and private construction in the United States and each state in 2021. Source: estimated by this study based on USGS 2023; PCA 2016; this study.

CO_2 EMISSIONS FROM THE U.S. CEMENT INDUSTRY

The U.S. cement industry emitted around 80 Mt of CO_2 in 2021 (calculated based on data from USGS 2023 and U.S. DOE 2022). Calcium carbonate thermal decomposition—the main chemical reaction— produces 57% of CO_2 emissions associated with cement manufacturing. The other 43% of emissions can be attributed to energy use (figure 3).

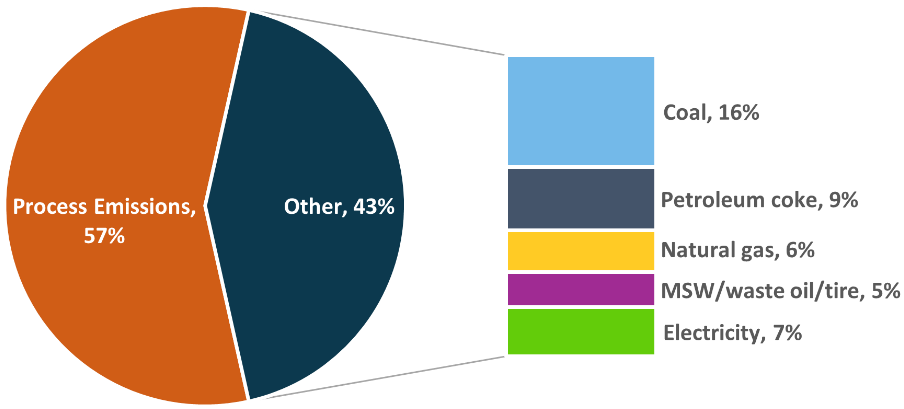


Figure 3. Shares of CO_2 emissions from the U.S. cement industry in 2021. Source: USGS 2023; EPA 2023.

The CO_2 emissions from the cement industry can be reduced by:

- Making energy efficiency improvements.
- Replacing portland cement to produce blended cements.
- Substituting portland cement in concrete with SCMs to produce lower embodied carbon concrete.
- Using alternative binding materials.
- Switching from traditional fuels to alternative fuels.
- Using renewable energy for electricity.
- Using decarbonized, alternative raw materials and feedstocks.
- Relying on electrochemical production.
- Implementing carbon capture and storage (IEA and WBCSD 2018, Goldman et al. 2023).

Other options, such as electrification and thermal storage, also offer potential reduction opportunities, but are in early-stage pilots and require additional support from industry, governments, and utilities to advance their implementation trajectories (Srinivasan and Elliott 2022).

The limestone calcined clay cement that is the focus of this report is a type of blended cement that can be used to substantially lower CO_2 emissions from the cement industry.

Supplementary Cementitious Materials

All the fuel and around 57% of the electricity used in a cement plant go toward clinker production (for raw material grinding, fuel preparation, and fueling the cement kiln). A higher clinker-to-cement ratio results in higher electricity and fuel intensity per metric ton of cement produced.

It should be noted that SCMs can be added during both cement production and concrete production. When we suggest or assume higher use of SCMs, this increase can be at either cement plants or concrete plants in the United States. We can replace portland cement with SCMs to make a blended cement (meaning less portland cement and thus less clinker is produced or used). This can help to significantly reduce energy intensity per metric ton of cement produced and reduce the energy and carbon footprint of the final product. We can also substitute SCMs for portland cement in concrete, which will similarly reduce the energy and carbon footprint of the final product. Different types of SCMs can be used in cement or concrete production. The most common SCMs are coal ash and slag, while other SCMs such as natural pozzolans, including calcined clay, have substantial potential for use in cement and concrete.

COAL ASH

Coal ash includes fly ash, bottom ash, and ponded ash. Fly ash is produced through a process of separating dust particles from flue gases emitted by coal-fired power plants. The use of fly ash in cement is dependent on the application, such as high-volume fly ash in mixtures for foundations and other mass concrete applications. Because fly ash is an industrial byproduct, substituting fly ash for a portion of portland cement in concrete production is associated with a lower greenhouse gas (GHG) footprint than using portland cement without fly ash and could also reduce the cost of concrete, depending on the available supply of coal ash in the region.

However, as the utility sector continues to shut down coal-fired power plants across the United States, the availability of freshly produced fly ash as a potential SCM is expected to decline over time. Harvesting coal ash (fly ash and bottom ash) from landfills and impoundments (ponded or recovered ash) has become a new source of SCMs for the concrete industry to compensate for the anticipated shortfall in new fly ash production, and the ASTM C618 standard was recently updated to accommodate the use of coal ash (ASTM 2022). In some states and U.S. regions (e.g., the eastern United States), in the near term, fly ash is expected to continue to be the less-expensive alternative to other SCMs. But in regions of the country (e.g., the western United States) that lack readily accessible landfilled sources of coal ash, other naturally available SCMs need to be considered (e.g., calcined, kaolinitic clay). Given the declining quantities of fly ash, reserving its use for specialized applications offers a productive pathway to use this SCM and leverage its traditionally recognized advantages such as enhanced durability, mitigation of alkali silica reactivity and sulfate attack, and reduced permeability to slow chloride ingress, thereby reducing corrosion (Thomas 2007).

SLAG

Another common SCM is slag, a by-product of iron production, used to make slag cement, formerly known as ground granulated blast furnace slag (GGBFS) cement. Slag cement as a sustainable construction material can be integrated into blended cement and concrete at higher proportions than other SCMs like fly ash. While European standards allow for up to 95% slag cement as a blended cement and U.S. standards and specifications allow as much as 80% (SCA 2024), the actual amount used in the United States is lower due to limited availability.

Slag's availability is limited in the United States because only around 29% of U.S. steel production comes from integrated plants with blast furnaces (which rely on coke, limestone, and iron ore) that produce slag cement, while the majority of U.S.-manufactured steel is produced by an electric arc furnace (EAF) process (which relies on electricity and recycled or scrap steel). As a result, slag cement is imported from countries like China, where 90% of steel is produced using the blast furnace-basic oxygen furnace (BF-BOF) process. However, the ongoing global shift away from blast furnaces to decarbonize the steel sector may affect slag cement availability in the coming decade.

Global clinker production is 8 to 12 times higher than global GGBFS production (Arnold et al. 2023). Domestic blast furnace slag production in 2018 was estimated to be between six and seven Mt (Curry 2021), which is less than would be required for use as an SCM in cement and concrete production even in the United States. Nonetheless, slag cement is available in certain regions and could be used in specialized applications where it offers advantages (e.g., reduced alkali silica reaction (ASR) in marine environments) to better harness this limited resource (Arnold et al. 2023).

NATURAL POZZALANS

Natural pozzolans are a type of SCM derived from natural deposits of magmatic materials such as pumice, volcano ash, and shale that can be used globally in the production of blended cements (which are based on portland clinker) and concrete. Although there are large reserves of natural pozzolans in the United States, they are less plentiful than other SCMs.

Prior to being used in the production of cement or concrete, at a minimum, natural pozzolans need to be dried and ground, which necessitates the use of both fuel and electricity. The amount of electricity required to grind natural pozzolans is almost equivalent to that needed for grinding the clinker that they replace, resulting in a negligible increase in electricity usage.

Natural pozzolan deposits are scattered geographically, making them hard to access, and the chemical and mineral compositions vary. Lack of infrastructure (e.g., paved road, rail connections, onsite electricity) and environmental permitting may delay their broader utilization. Although there may be a learning curve for cement and concrete producers in parts of the United States to use natural pozzolans, there is material-use experience available in the western United States and worldwide.

GROUND LIMESTONE

Ground limestone, although not an SCM, is a filler material currently used by cement plants worldwide (including in the United States) to produce portland cement (with up to 5% clinker replacement by limestone) and portland limestone cement (PLC), a blended cement (with 5–15% clinker replacement by limestone). It is estimated that cements using limestone as a filler represent 25–30% of global cement production, and that the share will increase by around 50% by 2050 (IEA and WBCSD 2018). Limestone is also the raw material for clinker production, so it is usually available near cement plants. When used as a filler, limestone is not calcined and instead just mechanically ground before addition, using less thermal energy, although the overall energy use would need to be evaluated in light of the energy used for mechanical grinding. In the United States it is common to grind the limestone with the clinker at the cement plant to create PLC. Although limestone is easier to grind than clinker, it must be ground more finely. Therefore, the time in the grinding mill is not necessarily shortened; it may, in fact,be lengthened. As a result, cement productivity is negatively impacted if the grinding capacity is balanced with (i.e., the same as) clinker production as it is at most cement plants. Cement plants are adding grinding capacity to address this issue. On balance, adding limestone as a filler to replace clinker uses substantially less energy, emits substantially less CO_2, and makes concrete slightly stronger and more elastic. In the past 10 years, there has been a substantial increase in the use of ground limestone in blended cements in the United States.

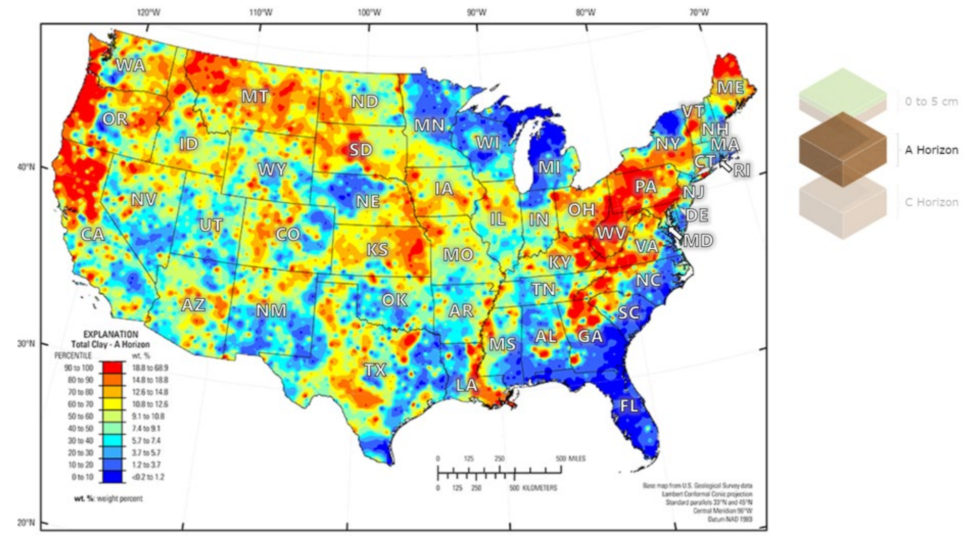
CALCINED CLAY

Calcined clay (from kaolinitic clays) is a type of natural pozzolan that can be used as an SCM in cement production to replace clinker or in concrete production to substitute portland cement. The energy needed to calcine one metric ton of raw clay is less than the energy needed to produce the amount of clinker the calcined clay would be replacing. This is because of the lower temperature needed to calcine clay (about 800°C) compared to traditional clinker production (around 1500°C) (LC3-Project 2023). The lower energy needed to calcine clay delivers environmental and emissions benefits, too, including greatly reduced CO_2 and other greenhouse gas emissions like sulfur oxides (SO_x) and nitrogen oxides (NO_x) due to reduced fossil energy (i.e., coal, petcoke) used for heat. Calcined clay has been in use since the Roman empire, but in the modern era, countries like the United States and Brazil have produced and used calcined clay since the mid-twentieth century. Early (i.e., one to three days) compressive strength of cement decreases when greater portions of calcined clay (e.g., impure kaolinitic clays) are used due to the slower reaction kinetics of this constituent compared to portland clinker in cement. However, recent developments suggest that an optimized combination of calcined clay and ground limestone as cement constituents (i.e., limestone calcined clay cement) could potentially result in up to 50% clinker displacement without affecting cement properties (i.e., in manageable ways with admixtures and other additives) (LC3-Project 2023).

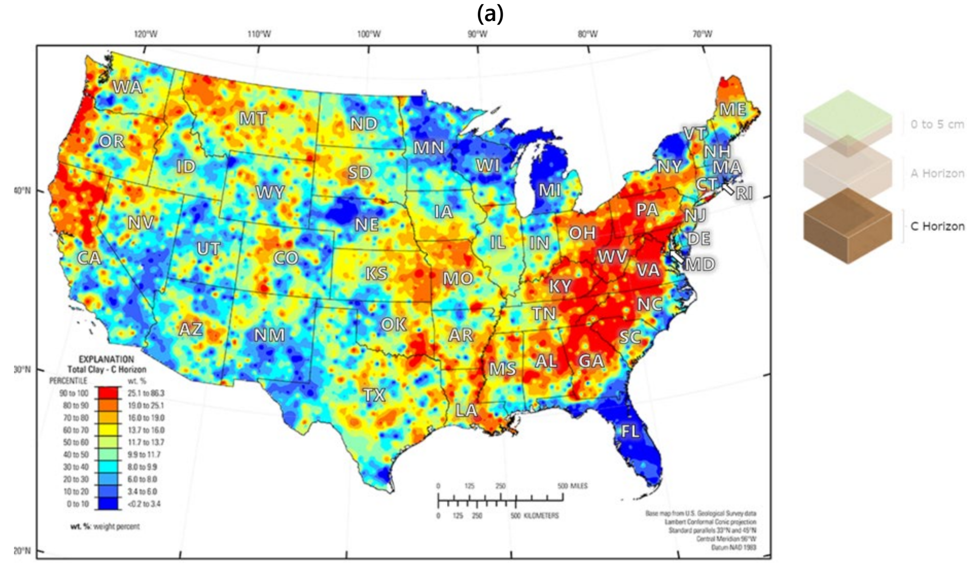
In considering the use of calcined clays in blended cements, the International Energy Agency (IEA) and World Business Council for Sustainable Development (WBCSD) project that limestone calcined clay cement, a blended cement made with calcined clay as an SCM, will account for more than a quarter of cement in the world by 2050 (IEA and WBCSD 2018). However, in the United States, calcined clays as an SCM are more often added to concrete at the concrete plant level. Clay is available abundantly in many U.S. regions (Smith et. al. 2019). Figures 4a and 4b show the distribution of clays in the United States. Among the large cement-producing U.S. states:

- Nine states have abundant (and in some cases higher-grade) clay availability (Alabama, California, Georgia, Kentucky, Maryland, Oregon, Pennsylvania, Virginia, and West Virginia).
- Eight states have adequate clay availability (Colorado, Nevada, New Mexico, Ohio, Tennessee, Texas, Utah, and Washington).
- The remaining states have local clay available to a lesser degree (Florida, Illinois, Indiana, Louisiana, Michigan, Montana, Nebraska, and New York) but would be able to acquire clays from adjacent or nearby states.

It's worth noting that ongoing geologic research supported by cement companies continues to unearth additional clay deposits in some of the states designated as being "less abundant," thereby moving states into categories of higher clay availability. Another point of note is that while some states, including Georgia, Kentucky, Florida, Tennessee, and California, have large kaolin deposits to produce high-quality metakaolin for the clay used in limestone calcined clay cement, this can still be an expensive material. Other states in the "adequate to lower availability" group, on the other hand, benefit from having lower-grade clays, which may be preferred for use in calcination processes due to their lower water demand and lower cost (compared to metakaolin). Clays may also be recovered from mine-tailings of raw materials mined for other industrial purposes, thereby taking advantage of recycled materials and circular economy and reducing the use of virgin mined raw materials.



(a)



(b)

Figure 4. Total clay in (a) A Horizon and (b) C Horizon in the United States, where red indicates higher concentrations of clay. Source: Smith et. al. 2019. Note: Soil A Horizon refers to the surface layer (typically 2–10" below ground) while C Horizon is the substratum (typically 30–48" below ground) (USDA 2022). Both horizons can be used to source clays through deposits or mining. Information about the sampling methods can be found in the Summary section of the source.

In considering the availability of clays compared to other SCMs, it is worth reiterating that fly ash and slag (discussed in earlier sections of this report) are much less available than clay in the United States. This is because coal accounts for less than 20% of U.S. power generation, and primary blast furnace-basic oxygen furnace (BF-BOF) steelmaking accounts for 29% of total U.S. steel production. Furthermore, the share of both coal-fired power generation and BF-BOF steelmaking is expected to decrease substantially in the coming years. That will make the fly ash and slag even more scarce. Figure 5 shows the relative availability of SCMs globally. The ratios of the SCMs globally generally represent those in the United States, as well (U.S.-specific data are not currently available).

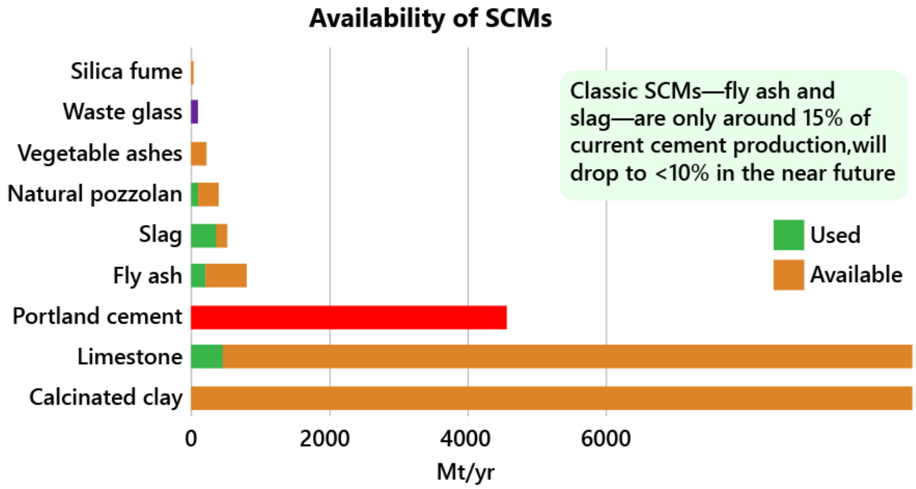


Figure 5. Relative availability of SCMs globally (Mt/yr). Source: Adapted LC3-Project 2023.

Limestone Calcined Clay Cement

WHAT IS LIMESTONE CALCINED CLAY CEMENT?

Limestone calcined clay cement is a low-carbon alternative to standard portland cement; it can cut CO_2 emissions related to cement manufacturing by up to 40% by reducing the amount of clinker and replacing it with limestone and calcined clays (LC3-Project 2023). Limestone calcined clay cement is a blended cement where the synergy between calcined clay and limestone allows for the reduction in clinker factor (percentage of clinker in cement) by 50% (figure 6). This reduction in the clinker factor in cement has emerged as a promising solution for CO_2 emissions reduction from cement and concrete production in the near term. Limestone calcined clay cement has been tested extensively and is proven to reach portland cement performance, making it a highly efficient and reliable option for construction projects (Krishnan et al. 2019; LC3-Project 2023).

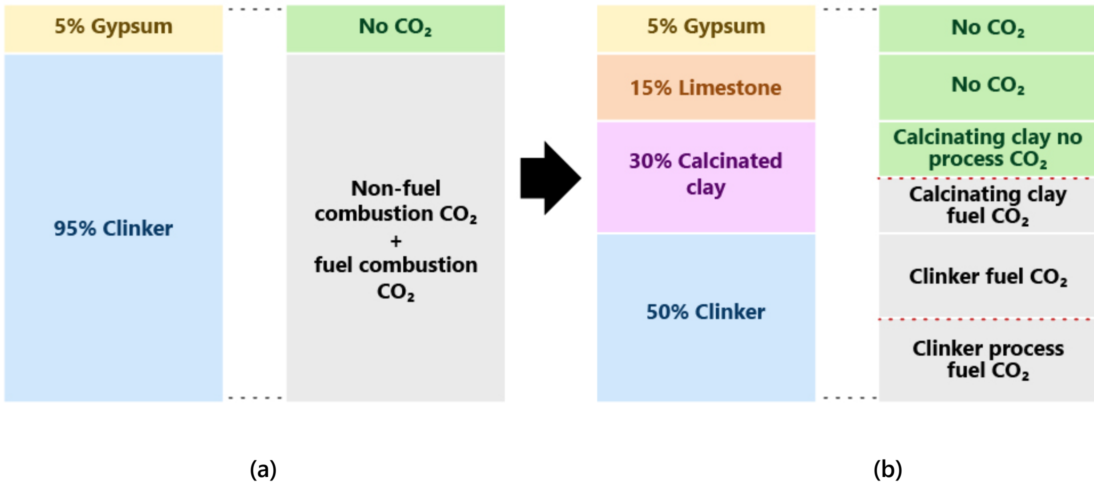


Figure 6. Schematic of material mix (left columns) and associated CO_2 emissions (right columns) of (a) portland cement compared to (b) limestone calcined clay cement. Source: Adapted LC3-Project 2023.

Limestone calcined clay cement is globally scalable as its constituent raw materials, limestone and calcined clay, are abundantly available worldwide, unlike other commonly used SCMs such as fly ash or slag. With their wide supply regions, transportation costs and emissions are also reduced. Additionally, limestone calcined clay cement is cost effective, with production costs up to 25% lower than portland cement due to savings in energy and materials. Calcined clay can be produced by repurposing existing equipment like rotary kilns, thereby avoiding the high capital cost of new plant builds by using equipment in traditional cement plants. Limestone calcined clay cement is ready to be implemented and is already being produced in several plants worldwide, making it a highly attractive option for the cement industry to reduce its carbon footprint. Limestone calcined clay cement provides the required concrete strength and improves durability. It can be used in a wide range of structural applications, such as residential buildings, commercial buildings, bridges, roads, pavements, and parking lots, with case studies showing that it meets strength requirements and emits less CO_2 over the lifecycle than portland cement (Cancio Díaz et al. 2017; Barbhuiya, Nepal, and Das 2023).

Limestone calcined clay cement has been found to have favorable mechanical properties, including strength similar to portland cement and more durability than other cement mixtures. Even though limestone calcined clay cement may exhibit slightly lower compressive strength in the earlier timelines (1–3 days), it can exceed the strength of portland cement a in longer time frame (e.g., 7–28 days) due to chemical reactions that occur during hydration. Limestone calcined clay cement also exhibits better durability than portland cement, particularly in terms of chloride resistance, alkali silica reaction resistance, and resistance to marine environments (Dhandapani et al. 2018, Pillai et al. 2019). Recycled aggregate concrete could also be combined with limestone calcined clay cement to achieve higher sustainability through a circular economy while maintaining sufficient mechanical properties (Guo et al. 2022). Ongoing research is being conducted to further advance the development and commercialization of limestone calcined clay cements (Sánchez Berriel et al. 2019).

STATUS AND ADOPTION OF LIMESTONE CALCINED CLAY CEMENT IN THE UNITED STATES

Limestone calcined clay cement is already covered in the ASTM International (ASTM) Standards C595 and C595M for Blended Hydraulic Cement and calcined clay as an SCM is covered under ASTM C618, hence it enjoys acceptance in the standards community. However, its application in the United States has been limited because of traditional construction practice and insufficient production and suppliers in the country.

Historical Use

Between 1908 and 1913, the Los Angeles Aqueduct was constructed using cement and concrete based on limestone, clays, and other carbonate rocks (W&PA 2024).

Figure 7. Los Angeles Aqueduct – First Cascade. Source: W&PA 2024.

In the 1930s natural pozzolans such as calcined shale (a mixture of clay, quartz, carbonates, and other materials) were used in the Golden Gate Bridge and Bay Bridge construction projects. The Golden Gate Bridge is still standing today and, while a new Bay Bridge was constructed to better accommodate seismological activity, the eastern span of the unused old bridge continued standing until it was dismantled in 2014. (QuakeTips 2013)

Figure 8. (a) Bay Bridge East Span (old), (b) Bay Bridge East Span (new), (c) Golden Gate Bridge, San Francisco, CA. Sources: (a) Eastern span of San Francisco-Oakland Bay Bridge. Photograph by Leonard G., 2004. Wikimedia Commons, Treasure Island, CA, (b) New and Old Bay Bridge. Photograph by Steve Jurvetson, 2013. Wikimedia Commons, Treasure Island, CA, (c) The Golden Gate Bridge and San Francisco, CA at sunset. Photograph by Brock Brannen, 2007. Wikimedia Commons, Marin Headlands, CA.

In the 1950s, according to the U.S. Bureau of Reclamation (USBR) construction history record, the Trenton Dam at the Colorado and Nebraska border was also built using a blended cement (viz. calcined clay and a Type II low alkali cement) produced by Ash Grove's Louisville Plant located in Nebraska. Active research is ongoing to understand the performance of the operational structure after 70 years of service.[1]

State DOT Experience with Calcined Clays and SCMs

State departments of transportation (DOT), which typically drive 50% of the construction in a state and use large quantities of concrete in infrastructure projects, have been studying supplies of traditionally used SCMs like fly ash and evaluating options for alternate SCMs to meet their demand needs. Here we describe the efforts of two state DOTs with respect to understanding SCM availability and conducting pilot studies.

California State DOT (Caltrans)

Caltrans represents one of the largest concrete-producing and -consuming markets in the United States. Members of the industry Rock Products Committee (RPC) gathered data from several national sources and explored several SCM options.

[1] Qi, Chengqing, Technical Center Director at Ash Grove Cement Company, a CRH Company. 2024. Personal communication.

- **Diminishing Fly Ash**. Caltrans found that in 2000, about 59 Mt fly ash was produced in the United States and 19 Mt were consumed; by 2015, fly ash production decreased to 45 Mt while consumption increased slightly to 21 Mt (Caltrans 2016). The report found that several factors impacted the fly ash shortage, including decreased coal usage due to lower electricity demand caused by unusually warm weather, seasonal maintenance shutdowns, economic shutdowns from switching to natural gas power plants and increased hydropower capacity, shutdowns from environmental regulations, and renewable energy targets. California's renewable energy policy, as outlined in Senate Bill 100 (2018), sets an ambitious goal of achieving 60% renewable energy by 2030 and mandates a transition to 100% zero-carbon or renewable sources for all retail electricity sales and state agency usage by 2045 (CEC 2023). All of this impacts the production of new fly ash.
- **Calcined Clays**. In considering calcined clays like metakaolin, a Caltrans assessment noted the advantages it offered—namely high strength, reduced permeability, and resistance to alkali silica reactions (ASR) and other chemical reactions—while acknowledging the lack of industrial infrastructure (in both manufacturing and transportation) that limits the possibilities of using metakaolin as a viable (i.e., at scale) SCM in California despite being acceptable in the specified standards within Caltrans (Caltrans 2016). In fact, according to recent reports, Caltrans is finalizing a new Approved Materials List (AML) category for blended cements, which will include limestone calcined clay cement. Additionally, Caltrans is looking to include LC3-types (similar to the LC3 composition but not exactly the same) in a new AML category.
- **Other SCM Options**. Caltrans assessments have also evaluated other SCMs, such as silica fume, rice husk ash, and recycled glass (Caltrans 2016, 2021).
- **Other State DOTs**. The issues described by Caltrans may be extrapolated to other regions of the United States, as well. Eight state DOTs (California, Colorado, Florida, Illinois, Nevada, Oregon, Texas, and Virginia) allow metakaolin in their AMLs despite ASTM and American Association of State Highway and Transportation Officials (AASHTO) standards covering metakaolin as an SCM (Sadati and Moore 2021). Thus, there is interest at the state DOT level in pursuing calcined clays, but this interest must be further built out.
- **Need to Increase Production Capacity**. In 2021, Caltrans concluded that the nation as a whole had a low capacity to build out clay production for the concrete industry (Sadati and Moore 2021). However, since then companies have increased their activities in an effort to increase the supply and use of calcined clay in the United States. Issues like these point to the need to build out U.S. production infrastructure for calcined clays.

The Minnesota (Mn) DOT

MnDOT is currently in the process of conducting a pilot of several different concrete products as part of its MnROAD Initiative in partnership with the National Road Research Alliance (NRRA), which operates in 14 states and is designed to test new technologies in a real-world environment. The MnROAD demonstration project is seen as a critical step toward a transition to new materials for road and infrastructure construction and is strongly supported by the Federal Highway Administration (FHWA), MnDOT, and industry (MnROAD 2024).

- **Limestone Calcined Clay Cement**. One of the products tested in the Minnesota pilot was a non-traditional blended hydraulic cement, which was expected to be limestone calcined clay concrete (consisting of 50% portland cement clinker, 15% ground limestone, 30% calcined clay known as LC3), but ended up being a blended cement concrete mix (with 30% calcined clay but not including 15% limestone) (Sutter and Van Dam 2022). This represents the first pilot application of limestone calcined clay concrete in the United States in which the state DOT specifications team is concurrently working with the pilot to draft specifications for the new material based on real-world results.
- **General Project Requirements**. These were designed to ensure portland limestone mixes use an ASTM C595 Type IL (10) blended cement, (and also separately test PLC with a 20% limestone addition not currently allowed in C595), that mixtures would meet performance requirements-based AASHTO R 101 “Developing Performance Engineered Concrete Pavement Mixture” (requiring 500 psi flex at 28 days, 5–8% air), that the product was batched and mixed at a central plant, and that it was paved using slip form paving equipment (Sutter and Van Dam 2022).
- **Pilot(s)**. The program consists of a section of pavement 250 ft long by 27 ft wide (2 lanes and shoulders) being paved with the calcined clay concrete product and being evaluated for performance over a two-year period and a lifecycle assessment (LCA). The pilot included identifying material providers, establishing mixture requirements, managing trial batching, and structuring a testing program. Initial results appear to indicate good compressive strength and other early performance characteristics (Sutter and Van Dam 2022).
- **Measurement and Reporting of Emissions.** An LCA evaluates the GHG emission impacts of a product (including its embodied emissions) and forms the basis for developing product category rules and environmental product declarations (EPD). EPDs communicate the environmental performance or impact of a product. EPDs are specific to the region where a product is manufactured and are not available for limestone calcined clay cement in the United States because of the requirement that a production facility must be in continuous operation for at least one year before an EPD may be generated for inclusion in the Building Transparency-operated Embodied Carbon in Construction Calculator EPD database and repository.
- **Impacts on Market Acceptance.** Without EPDs for blended SCMs, it is challenging to quantify the GHG reduction when trying to compare reductions between a product using calcined clays and one using fly ash. Fly ash EPDs show no GHG emissions since they are considered a by-product of coal-fired power plants, which is where the GHG emissions are assigned. To advance market acceptance of newer lower-embodied-carbon products, there are efforts to shift the one-year requirement when data is not yet available by enabling the use of provisional or predictive EPDs, and EPDs are currently being

developed for blended SCMs. The FHWA is working with the National Renewable Energy Laboratory's LCA Commons database to provide the necessary lifecycle inventory data for EPD development (Sutter and Van Dam 2022).

Manufacturer Experience with Calcined Clays

In 1997, one company, Ash Grove Cement, created a cementitious product by inter-grinding a calcined high-quality kaolin with clinker and optimized gypsum content, branded as Duracem® N. Subsequently, in the 2000s, because Class F fly ash was abundant in the market at a low cost, the cementitious product switched to using fly ash. As high-quality fly ash has become less available and more costly, calcined clay use was resurrected in 2017 to reintroduce a blended cement with calcined clay, which falls under the Class N designation for natural pozzolan in ASTM C618 (Ash Grove 2023). Reportedly, the company plans to convert an existing rotary kiln to produce calcined clay cement and limestone calcined clay cement.

As of 2023, another company has developed a metakaolin-based (a type of clay) SCM that has been tested as a natural pozzolan, meeting all the requirements of both ASTM C618 and AASHTO M295 (Purebase 2023a). Recently, the same company installed a Phase I calciner in its Ione California plant to produce calcined clay as an SCM and plans to submit its SCM for evaluation by Caltrans and inclusion in the Caltrans AML (Purebase 2023b). The company also hosted the California Air Resources Board (CARB) at its plant to share how it plans to roll out its metakaolin and blended SCM (based on metakaolin) products and reduce GHG emissions in accordance with CA SB596 (Purebase 2023c). The blended SCM (potentially as a limestone calcined clay blend) may serve as a better replacement for fly ash or natural pozzolan and is intended for direct use by ready-mix producers.

Research Studies in the United States

Calcined clay SCMs have been tested in a few different, inter-related studies in the United States by universities working in conjunction with manufacturers:

- One study tested three calcined clays, three volcanic ashes (natural pozzolans), three ground bottom ashes, and two fluidized bed combustion ashes for their suitability in concrete use (Tokpatayeva et. al. 2022).
- Another study focused on the pozzolanic reactivities of the same set of 11 natural and non-conventional pozzolans (NNPs) (Yoon et. al. 2022).
- A third study looked at how effective 14 different SCMs (including the same set of 11 NNPs from Yoon 2022) are in reducing the risk of alkali-silica reaction (ASR) in a concrete pore solution (from 20% portland cement replacement in cement pastes), given that alkalis present in SCMs are also soluble in pore solutions, which can reduce their effectiveness (Rajabipour and Sharbaf 2024).

Calcined clay is of interest, especially with its higher cement replacement rate of 30-35% (by weight), despite differing levels of kaolinite content and purities. It needs to be further studied in concrete mixes used in construction applications (Tokpatayeva et. al. 2022). These previous studies have also confirmed that adding limestone to calcined clays optimizes its binding properties as an effective ternary blended SCM (Tokpatayeva et. al. 2022; Yoon et. al. 2022) and that it can increase the portland cement replacement rate up to 50%. The effectiveness of an SCM in binding alkalis out of pore solution has also been found to significantly depend on its soluble alkali content, pozzolanic reactivity, and effect on calcium (alumino) silicate hydrate (Ca/(Si+Al)) formation, and some calcined clay SCMs are more effective in reducing ASR (Rajabipour and Sharbaf 2024).

Metakaolin SCM appears to be suitable for use in concrete, given its properties and test results higher than other SCMs in early-age compressive strengths, total heat value, replacement of consumed carbon-hydrogen at 28 days, and average compressive strength at seven and 28 days (Tokpatayeva et. al. 2022; Yoon et. al. 2022; Rajabipour and Sharbaf 2024; Purebase 2023b).

International studies have demonstrated up to 40% replacement rates, but in the United States work in this area is still ongoing. The three studies cited above are examples of a larger body of research that is ongoing at several universities independently in conjunction with different manufacturers, testing different mixes and confirming their mechanical and performance attributes.

Overall, interest in limestone calcined clays has grown in recent years due to increasing government support and investment in industrial decarbonization. The topic is increasingly discussed in conference presentations, workshops, and reviews of pilots and demonstration projects at the American Concrete Institute Meetings in 2022 and 2023, the Getting to Zero Forum (2023), and others anticipated in 2024.

INTERNATIONAL CASE STUDIES FOR LIMESTONE CALCINED CLAY CEMENT

The use of limestone calcined clay cement has been studied in several countries around the world, including India, Brazil, Colombia, and Cameroon. We explore international case studies on the use of limestone calcined clay cement in different countries and discuss the findings and implications of these studies. They were selected to showcase geographic variation around the world (five continents), length of time (from 2014 to now), and the range of test results in different applications, environments, and industrial infrastructure capacity. Additional details about the specific applications from these studies, where available, are included in Appendix A.

India

One of the earliest and most extensive case studies on the use of limestone calcined clay cement was conducted in India. The study was funded by the Swiss Agency for Development and Cooperation, and it involved the construction of a building using limestone calcined clay cement as the primary binder. The concrete produced from limestone calcined clay cement had a compressive strength of 40 MPa, which is comparable to concrete from traditional portland cement (Bishnoi et al. 2014). More recent developments have built on the promising performance results of limestone calcined clay cement, including plans to produce the material. J.K. Lakshmi has been planning production since 2016 and expects its produced material to offer a 30–40% reduced carbon footprint (LC3-Project 2017; Global Cement 2024).

China

In China, researchers conducted a case study on the use of limestone calcined clay cement in concrete production and found that it had a compressive strength that was comparable to concrete produced from portland cement. The researchers found that limestone calcined clay cement could be used in high-stress applications and could help reduce the carbon footprint of infrastructure projects in China (Huang et al. 2020).

Brazil

In Brazil, a case study was conducted to compare the performance of limestone calcined clay cement and concrete to traditional portland cement and concrete in the construction of a residential building. The concrete produced from limestone calcined clay cement had a compressive strength of 47 MPa, which was slightly higher than the concrete produced from portland cement. The concrete produced from limestone calcined clay cement also had a carbon footprint up to 38% lower than the concrete produced using traditional portland cement (Euler, Braga, and Barata 2023).

Colombia

In Colombia, Argos has developed commercial production of limestone calcined clay cement in its Rioclaro cement plant, where it opened a calcined clay line in 2020. It was reported that the technology has reduced energy consumption by 30% and carbon emissions by 38% compared to portland cement (LC3-Project 2020; Edwards 2020). According to Edwards, the Rioclaro plant is the first of its kind to reach such large scale, producing calcined clay at a capacity of 0.45 Mt/yr, after smaller trials were explored in Cuba, India, and Switzerland (2020).

Cuba

Case studies of limestone calcined clay cement in Cuba aimed to assess the material's economic and environmental potential in the Cuban context. The study was conducted collaboratively by the Central University "Marta Abreu" of Las Villas' Centro de Investigación y Desarrollo de Estructuras y Materiales (CIDEM) and the Laboratory of Construction Materials at École Polytechnique Fédérale de Lausanne (EPFL). The Cuban cement industry has been using limestone calcined clay cement since 2011 and has found it to be a promising solution to meet the growing demand for cement while reducing GHG emissions. The study compared limestone calcined clay cement with traditional portland cement and the current commercial blended cement with zeolite sold in Cuba. Results showed that limestone calcined clay cement reduced production costs in the range of 15–25% compared to conventional solutions and reduced GHG emissions up to 20–23% compared to business-as-usual practice (Cancio Díaz et al. 2017; Sánchez Berriel et al. 2016). One company

(Geominera del Central), in research collaboration with CIDEM, has started to produce limestone calcined clay cement at a rate of seven t/day (Global Cement 2019).

Ivory Coast

A Turkish company and its subsidiary (Oyak Çimento and Cimpor, respectively) commissioned a limestone calcined clay cement plant in mid-2020 (Perilli 2022). Located on the western coast of Africa in the city of Abidjan, Ivory Coast, the plant produces 0.3 Mt/yr of calcined clay but has a capacity of 2,400 tons of cement per day or 0.88 Mt/yr through its grinding production line (Perilli 2022).

Ghana

Ghana has also started to produce calcined clay cement, encouraged by its neighbor, Ivory Coast, which promoted the use of limestone calcined clay cement to the Ghana Standards Authority (Perilli 2022). In fact, CBI Ghana, a cement manufacturing company, has signed an $80 million contract to build one of the largest calcined clay cement plants in the world, expected to produce 0.405-0.6 Mt/yr and create hundreds of jobs for Ghanaians (CBI Ghana 2022; Global Cement 2024). In addition to 30–40% clinker substitution to reduce the environmental impact of cement production, FLSmidth is expected to install a new clay calciner system in the CBI facility to help substitute clinker and attain a 60–70% replacement level (Rajo and Lalit 2023). The calcined clay cement plant also reduces the need to import clinker and portland cement because of the availability of Ghanaian clay near the project site (CBI Ghana 2022).

Australia

There have not yet been any pilots for limestone calcined clay in Australia, but several universities have been conducting studies to check its suitability for use in the country. The University of New South Wales in Sydney has recognized the urgent need for decarbonizing the cement industry, hoping to transition from fossil fuels to renewables and to low-carbon cement alternatives and SCMs (Centre for Infrastructure Engineering and Safety 2023). The Centre for Infrastructure Engineering and Safety has conducted various chemical and mechanical tests in its laboratories to explore the feasibility of limestone calcined clay cement in Australian construction because of clay's abundance in the country (Centre for Infrastructure Engineering and Safety 2023). The University of Queensland launched a limestone calcined clay cement feasibility project in 2021 with the Australian Institute for Bioengineering and Nanotechnology, along with two research institutes from India (the Indian Institute of Technology Delhi (IIT Delhi) and Technology and Action for Rural Advancement (TARA)), learning from the Indian researchers' recent limestone calcined clay cement work in other countries such as Cuba and Malawi (SMI 2023).

France

France has become home to Europe's first calcined clay production line, launched by Holcim in early 2023. The new cement plant boasts CO_2 reductions of 50% and runs on 100% biomass fuel with a waste heat recovery system. This plant has an expected yearly output of up to 500,000 tons of ECOPlanet cement and is part of Holcim's decarbonization roadmap for European construction (Holcim 2023).

Appendix B summarizes the most recent limestone calcined clay projects by continent. There are close to 45 known projects worldwide that have plans to begin, or have already begun production, revealing increasing demand for limestone calcined clay. In North America, Europe, and Africa, progress is developing rapidly, with new projects in both manufacturing and demonstrations coming online within the next two years. In Central America, the Caribbean, and South America, progress is slower due to less readily available resources of clays and standards not yet in place for clinker substitution at more than 50%. While India's newer standards are kickstarting many projects, the rest of Asia, including Southeast Asia and China, is more resistant to reducing its clinker factor due to shrinking markets and perceived risks of using limestone calcined clay cements.[2]

These international case studies provide evidence for limestone calcined clay cement's potential as a sustainable replacement of a portion of traditional portland cement through its use in several test projects. In turn, cement companies, which are international conglomerates with operations in the United States and other countries, are establishing calcined clay cement production lines and plants in some of their other markets globally, pointing to the general maturity of the technology, availability of raw materials, and anticipation of widespread commercial use that comes with growing confidence in performance testing results. While further research is needed to fully evaluate the performance and long-term durability of limestone calcined clay cement, these studies (also summarized in the Appendix) suggest that limestone calcined clay cement will play an important role in reducing the carbon footprint of the construction industry around the world, particularly in the global south where limestone reserves are more limited, which drives higher prices for clinker imports in these countries. Additional pilots across a range of construction applications, production and ready availability of the building material, and incorporation in construction codes and standards in the United States (e.g., state DOT AMLs) would further advance its use in the U.S. market.

[2] Scott Shell, Associate Director of Industry at ClimateWorks Foundation. 2023. Personal communication.

The CO_2 Emissions Reduction Potential of Limestone Calcined Clay Cement in the United States

This analysis of CO_2 emissions reduction potential of limestone calcined clay cement in the United States takes into account the carbon intensity of the replacement blended cement, different market adoption scenarios, and the share of concrete procured in the United States by government-owned funds (federal, state, local) and the private sector. The analysis focuses only on the material efficiency impacts of limestone calcined clay cement replacement at this time, without consideration of the reduction in thermal energy requirements or the use of clean energy for electricity. Table 1 summarizes the analytical results across the scenarios, with detailed results following in this section.

Table 1. Summary of CO_2 reduction potential of limestone calcined clay cement procured by governments and the private sector in the United States.

	Limestone calcined clay cement market adoption rate				
	None (BAU)	Low (10%)	Medium (20%)	High (30%)	Transformative (50%)
Annual CO_2 reduction potential from government procurement only (Mt CO_2)	0 Mt CO_2	1.5 Mt CO_2	2.9 Mt CO_2	4.4 Mt CO_2	7.3 Mt CO_2
CO_2 emissions of the U.S. cement industry in 2021 avoided from government procurement only (%)	0%	2%	4%	6%	9%
Annual CO_2 reduction potential from private procurement only (Mt CO_2)	0 Mt CO_2	1.7 Mt CO_2	3.5 Mt CO_2	5.2 Mt CO_2	8.6 Mt CO_2
CO_2 emissions of the U.S. cement industry in 2021 avoided from government procurement only (%)	0%	2%	4%	6%	11%
Total annual CO_2 reduction potential from government and private procurement (Mt CO_2)	0 Mt CO_2	3.2 Mt CO_2	6.4 Mt CO_2	9.6 Mt CO_2	15.9 Mt CO_2
Total CO_2 emissions of the U.S. cement industry in 2021 avoided from government and private procurement (%)	0%	4%	8%	12%	20%

Assumptions:

1. **A 45% replacement rate of limestone calcined clay cement in portland cement, which leads to a 40% lower carbon intensity for limestone calcined clay cement compared to portland cement (business as usual, BAU).**
2. **Government (federal, state, local) procured concrete accounts for 46% of total procurement and the remaining 54% is procured by the private sector.**
3. **Market adoption rates in each scenario of 10%, 20%, 30%, 50% create a range of emission reductions based on level of adoption from low to transformative.**
4. **Estimates only emissions reductions due to material efficiency, not improvmements in energy efficiency or the use of clean energy for electrical processes (including grinders, calciners, etc).**

U.S. CO_2 emissions can be reduced by as much as 7.3 Mt annually if federal, state, and local governments shift half of their procurement of cement to limestone calcined clay cement. The potential CO_2 emissions reduction impacts from the adoption of limestone calcined clay cement in the U.S. market would more than double (8.6 Mt) if we consider the potential impact from the limestone calcined clay cement used in non-public construction projects. The total annual CO_2 emissions reduction amounts to 15.9 Mt of CO2, which accounts for 20% of the avoided emissions from 2021 baseline year.

Figure 9 shows annual CO_2 emissions associated with cement used in all 50 U.S. states in 2021. We used the weighted average CO_2 intensity of cement produced in the United States and net imported cement to calculate annual CO_2 emissions associated with cement consumption. Around half of the annual CO_2 emissions linked with cement consumption are associated with public construction, which was approximately 36.5 Mt CO_2 in 2021 (figure 9). Therefore, government procurement offers significant leverage in incentivizing decarbonization of cement production through various decarbonization measures, including the use of limestone calcined clay cement.

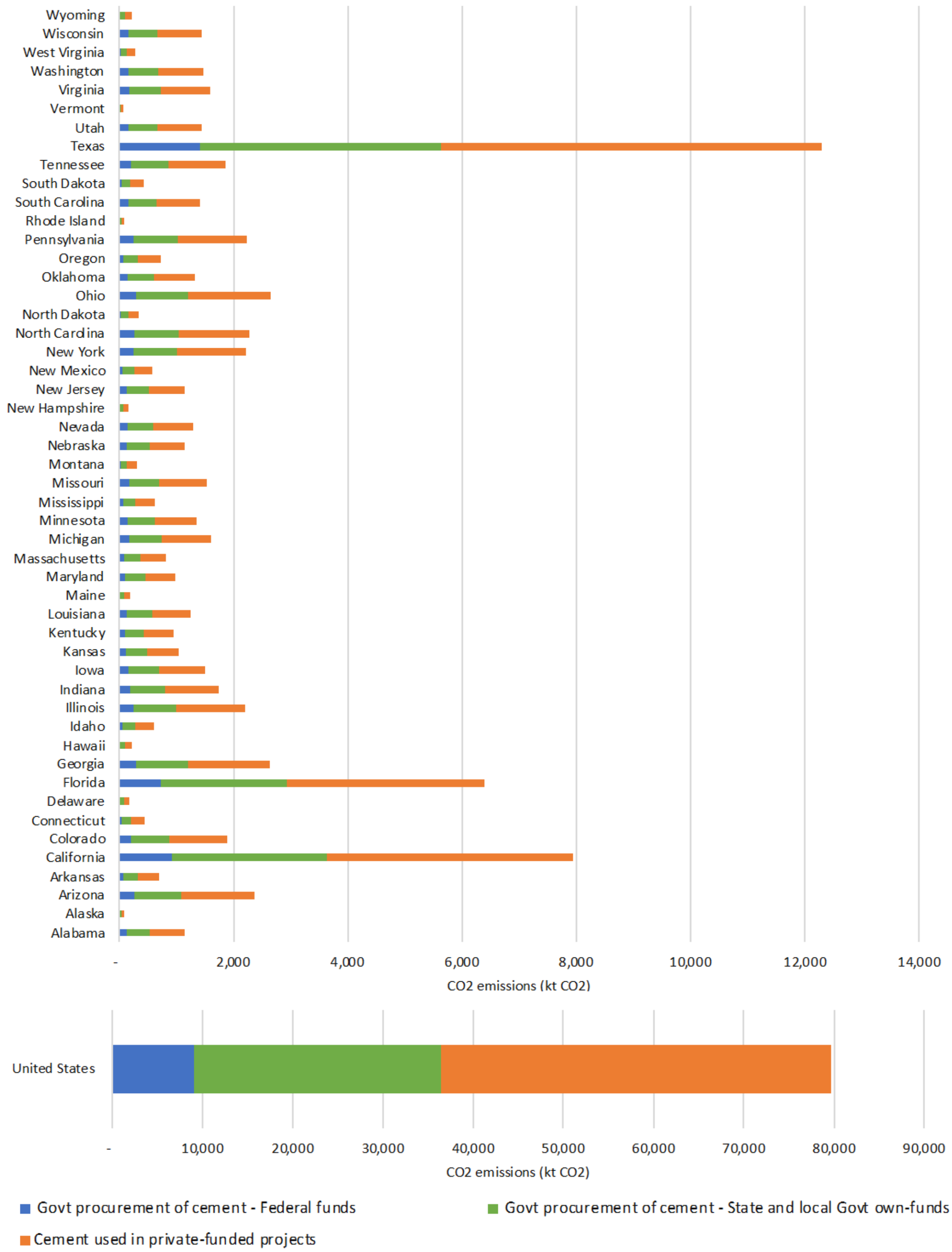


Figure 9. Annual CO_2 emissions associated with cement used in the United States and selected states as of 2021.

To estimate the potential impact of the use of limestone calcined clay cement on CO_2 emissions associated with U.S. cement use, we developed several scenarios with various rates of adoption for limestone calcined clay cement as a percentage of total cement demand in the United States and selected states (table 2). This scenario analysis functions as a sensitivity analysis and offers a way to evaluate emissions reductions based on differing rates of adoption of limestone calcined clay cement in the absence of green public procurement policy covering this new product in most states.

Based on the share of portland cement that limestone calcined clay cement replaces in each scenario, we calculated an average cement CO_2 intensity for the cement used in the United States and the 50 states. We assumed the CO_2 intensity of limestone calcined clay cement is 40% lower than the CO_2 intensity of portland cement (Krishnan et al. 2019; LC3-Project 2023). It should be noted that a CO_2 intensity reduction of up to 50% is also possible for limestone calcined clay cement without consideration of the added benefits of electrification.

Table 2. Limestone calcined clay cement adoption scenarios for the cement industry in the United States. Source: this analysis, DOE 2022.

Scenario	Share of total cement demand replaced with limestone calcined clay cement	Average cement CO_2 intensity (kgCO_2/t cement)
Baseline	-	750
Low	10%	720
Medium	20%	690
High	30%	660
Transformative	50%	600

Using the annual CO_2 emissions associated with cement use in the United States presented above and the scenarios defined in table 2, we estimated the annual CO_2 emissions reduction potential resulting from limestone calcined clay cement adoption in the United States and all 50 states under different scenarios based on 2021 emissions data (figures 10–12).

Figure 10 shows the annual CO_2 reduction potential under different limestone calcined clay cement market adoption scenarios. Under the low scenario (10%), an annual emissions reduction of 1.5 Mt CO_2 can be achieved directly from government procurement of cement for construction in the United States. This annual CO_2 emissions reduction potential in the United States from government procurement of cement would increase to 2.9 Mt CO_2, 4.4 Mt CO_2, and 7.3 Mt CO_2 per year under the medium (20%), high (30%), and transformative (50%) scenarios, respectively.

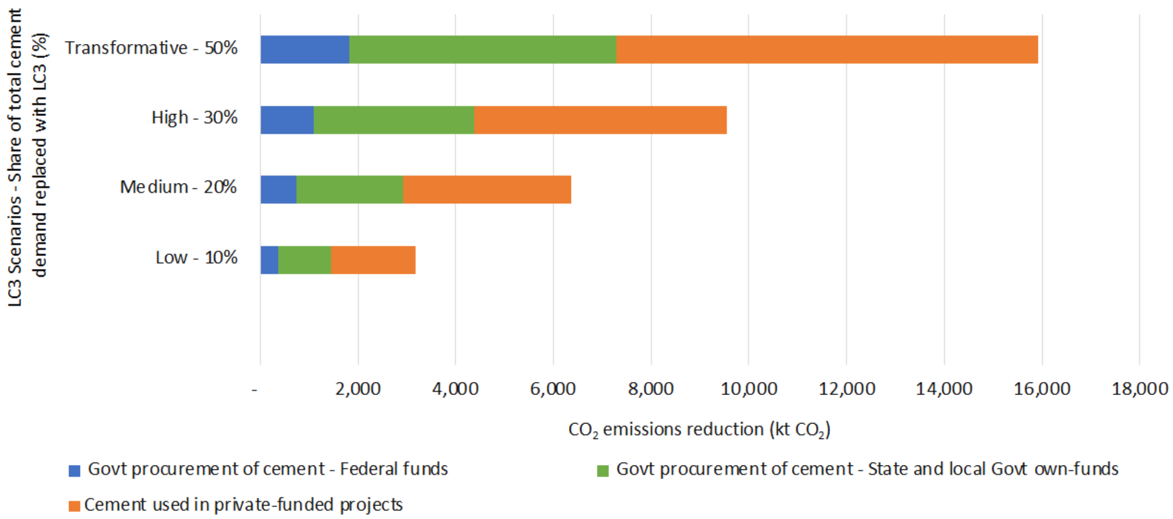


Figure 10. Annual CO_2 emissions reduction potential resulting from limestone calcined clay cement market adoption under different scenarios in the United States in 2021.

The potential impacts of limestone calcined clay cement adoption in each state are also shown in figures 11–12. The relevance of each of the four scenarios to a particular state will depend on climate policy, existence of Buy Clean or performance-based concrete procurement policies, availability of suitable clay reserves, and other factors.

Under the low scenario of limestone calcined clay cement adoption (10%) shown in figure 11, the potential annual emissions reduction ranging from 0.001 to 0.23 Mt CO_2 can be achieved across the 50 states directly from government procurement of cement for construction, with the three highest-producing and -consuming states of Texas, California, and Florida showing 0.23 Mt CO_2, 0.15 Mt CO_2, and 0.12 Mt CO_2 reductions per year, respectively.

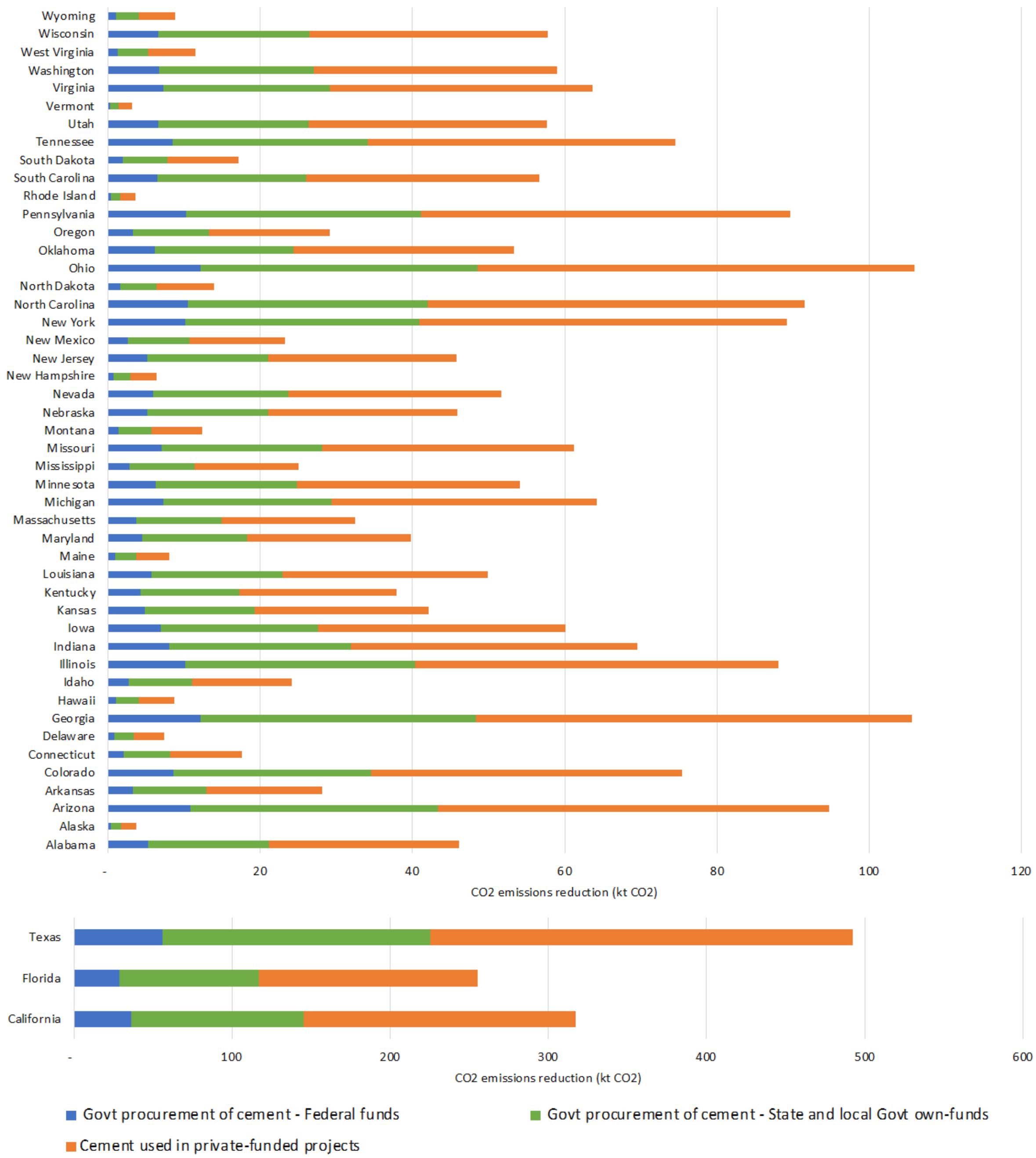


Figure 11. Annual CO_2 emissions reduction potential compared to 2021 resulting from limestone calcined clay cement adoption in select states – low scenario (10% of cement consumption replaced with limestone calcined clay cement).

Under the medium (20% adoption) and high scenarios (30% adoption), this CO_2 emissions reduction potential doubles and triples, respectively (see Appendix C).

In the transformative scenario of limestone calcined clay cement adoption (50%) shown in figure 12, the potential annual emissions reduction ranging from 0.007 to 1.1. Mt CO_2 can be achieved across the 50 states directly from government procurement of cement for construction, with the three highest-producing and -consuming states of Texas, California, and Florida showing 1.1 Mt CO_2, 0.73 Mt CO_2, and 0.58 Mt CO_2 reductions, respectively.

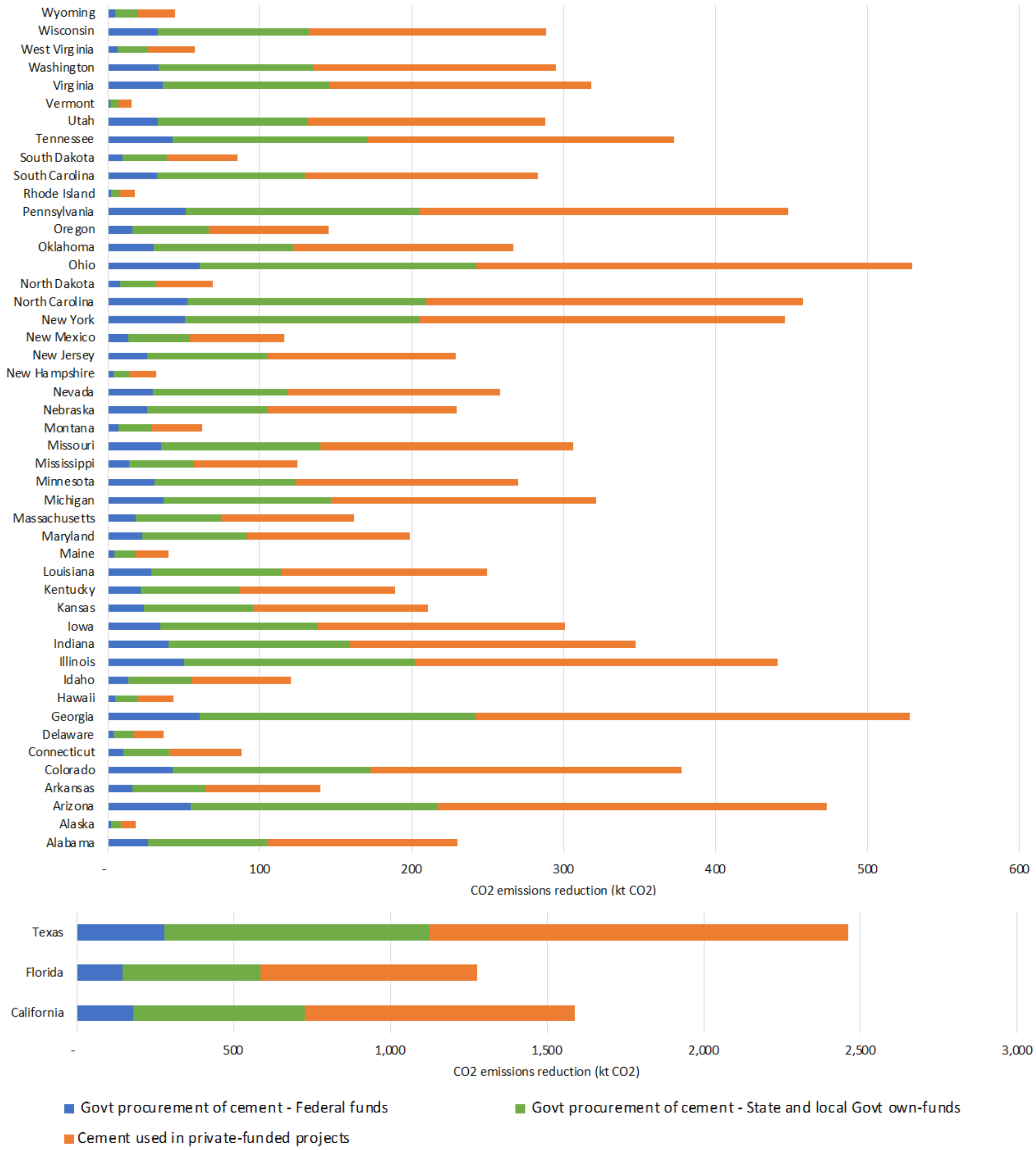


Figure 12. Annual CO_2 emissions reduction potential resulted from limestone calcined clay cement adoption in the selected states in 2021 – transformative scenario (50% of cement consumption replaced with limestone calcined clay cement).

Other Benefits of Adopting Limestone Calcined Clay Cement in the United States

PATHWAY TO ELECTRIFICATION

The use of calcined clay in blended cement or as an SCM represents a material efficiency approach to reduce embodied carbon emissions in cement and concrete. About half of the cement production emissions arise from the calcination of limestone to produce clinker, so calcined clay, which is not a carbon-based material, helps to substantially reduce CO_2 emissions. It can also enable greater reductions in carbon emissions from this sector through energy efficiency due to its lower temperature requirement—at less than 800ºC—compared to the 1500ºC of traditional portland cement. This lower temperature requirement makes process electrification for clay calciners more feasible, especially when coupled with thermal storage technologies that are starting to enter the market. The electrified clay calciner is already commercial technology and is being evaluated for use by some cement and clay calcining companies. If an electrified calciner is used to produce calcined clay and the electricity is supplied from renewable sources, then zero-carbon calcined clay can be produced.

To estimate the full emissions reduction potential, we start with a baseline: limestone calcined clay cement, a blended cement, produced by fossil fuel-based conventional calciners offers a 40% reduction in emissions over conventional portland cement. Electrification of the clay calciner, powered by renewable energy, can help produce zero-emission calcined clay. If this zero-emission calcined clay is used in limestone calcined clay cement production, then emissions reduction can be as high as 50%.

According to the U.S. Department of Energy (DOE) Pathways to Commercial Liftoff: Low-Carbon Cement report, electrification of traditional precalciner/kiln technologies used in conventional portland cement production may achieve up to a 35% reduction in carbon emissions (Goldman et al. 2023). Thus, if clinker is also produced by an electrified precalciner/kiln using renewable or clean process heat and is coupled with zero-emission limestone calcined clay, then the limestone calcined clay blended cement would achieve about 70–75% emissions reduction compared to conventional portland cement.

Maturation of the calcined clay technology over time to include higher than 45% replacement rates in blended cement and concrete mix design efficiencies can further bring the total emissions reduction potential to 80% or higher in zero-emissions scenarios (compared to business as usual). Carbon capture, utilization, and storage (CCUS) can then be employed to reduce emissions further. These estimates underscore the importance of advancing research, development, demonstration, and commercial deployment of electrification technologies for the cement sector through the Inflation Reduction Act (IRA 2022), the Concrete and Asphalt Innovation Act (2023), and other policy initiatives.

BUSINESS CASE FOR MANUFACTURERS

Cement and concrete manufacturers and suppliers may derive several potential benefits by increasing their production of low-embodied-carbon products. Doing so may be considered a risk mitigation strategy to insulate themselves from the market pressure that arises from a rapidly changing policy environment at the federal and state levels (e.g., with Buy Clean public procurement). Developing low-carbon product lines would help shield manufacturers from the risk of loss that may come from customers switching from regular or higher-embodied-carbon construction materials to low-embodied-carbon products, changes in construction codes and standards that specify low-carbon materials (e.g., state DOTs), and further changes to local, state, national, and international policies and regulations. The U.S. cement sector is predominantly represented by international conglomerates headquartered in European countries, some of which have established ambitious carbon reduction roadmaps.

Today, with a relatively high clinker factor in cement, the U.S. cement industry has room to make a significant impact on its sustainability commitments. Producing SCMs in-house helps avoid price swings while controlling product quality. In some instances, it may be less expensive than purchasing coal ash. Some of the newer coal ash SCMs may also demonstrate lower quality and inconsistent performance due to pollution control requirements, which in turn impacts the quality of a company's cement end product and may impact cost.

Transitioning to low-carbon material production offers manufacturers other benefits as well, such as increasing market competitiveness, helping with corporate climate disclosures, and helping meet GHG-reduction commitments that are required for scope 1, 2, or even 3 emissions. From a cost-benefit perspective, while the transition to new technologies and equipment would require additional capital investments in the short term, these investments could be offset by increased sales and lower costs from the lower energy requirement of limestone calcined clay cement production in the longer term. A proactive approach to economic and regulatory signals would enhance long-term sustainability and brand reputation while creating business opportunities that are aligned with market demand, environmental responsibility, and protecting shareholder investments (Srinivasan et. al. 2022).

STAYING AHEAD OF LOCAL AND STATE REGULATORY AND POLICY CHANGES

Several local government agencies have implemented portland cement and concrete mix design approval processes, based on maximum acceptable global warming potential (GWP), which has a major influence in transitioning to low-carbon material production. In 2019, the city of Portland, Oregon, for example, added EPD requirements for the supply of portland cement concrete for city construction projects (Portland 2023)., At the state level, California recently passed a climate disclosure bill that has the potential to affect almost 5,000 companies by requiring disclosures from their operations and supply chains (California State Senate 2023).

ENVIRONMENTAL JUSTICE AND COMMUNITY BENEFITS

As the sector transitions to low-embodied-carbon material production using limestone calcined clay cements, it will allow the training and re-skilling of workers in new green technologies and support workforce development in disadvantaged communities around plants. Reducing emissions will also improve public health for disproportionately impacted and historically disadvantaged communities that live near industrial and manufacturing establishments and may have heightened environmental exposures. This is a key requirement under federal funding announcements from DOE for industrial decarbonization projects in keeping with the Justice40 Initiative. The initiative's goal is to ensure that benefits from federal investments under legislation like the IRA flow to disadvantaged communities that are marginalized, underserved, and overburdened by pollution (The White House 2024).

Barriers to the Adoption of Limestone Calcined Clay Cement in the United States

The use of calcined clay in concrete has faced several barriers in the U.S. market.

Technical barriers include the fact that clay activated through either rotary kiln conversion or flash calciner needs process fine tuning and strategies for color management. The current cement operations have limited extra grinding capacities and process modification potential to attain optimized limestone calcined clay cement performance. Separate grinding of calcined clay and portland cement for particle size optimization may require further technical studies and capital expenditure investments. Limestone calcined clay cement can affect the workability of concrete and is dependent on the mix design (Barbhuiya, Nepal, and Das 2023). The substitution of portland cement by limestone calcined clay cement has led to a reduction in early-age (one and three days) compressive strength (which can affect construction schedules and costs), increased water demand, and lower flexural strength values. The lack of infrastructure for producing and distributing limestone calcined clay cement is another barrier (Wang et al. 2021; Ez-zaki et al. 2021).

Existing **construction industry standards and codes** for cement sometimes do not accommodate the use of alternative materials like calcined clay. This can make it challenging for limestone calcined clay cement producers to meet the required specifications, which can limit its adoption in the market. However, the ASTM C595/C595M standard for blended cements already allows for limestone calcined clay cement in the United States, where mixtures down to 45% clinker, up to 15% limestone, and up to 40% pozzolan fall within the requirements (Martirena Hernández and Scrivener 2019). Table 3 summarizes current standards that apply to calcined clay as an SCM and limestone calcined clay cements.

Table 3. Standards affecting limestone calcined clay cement adoption for the cement industry in the United States. Source: ASTM 2023a, b, c and AASHTO 2019.

Standard	Specification application	What it covers	Relationship to limestone calcined clay cement
ASTM C595	Blended hydraulic cements	Binary and ternary blended cements, limiting pozzolan content to 40% and limestone content to 15% by mass	Limestone calcined clay cement works best with 20% limestone, needs updating
ASTM C618	Coal ash and raw or calcined natural pozzolan for use in concrete	Covers Class F and C Coal Ash and Class N: Raw or Calcined Natural Pozzolan	Allows calcined clays as an SCM, no change needed
AASHTO M 295	Same as ASTM C618	Same as ASTM C618	Same as ASTM C618
ASTM C1157	Hydraulic cement	Hydraulic cement attributes (portland and blended) related to concrete performance meeting set requirements	Performance-based specification is favorable to limestone calcined clay cement, no change needed

State DOTs specify materials for use in public infrastructure projects on AMLs following rigorous evaluation in state DOT testing laboratories. While some states (California, Colorado, Florida, Illinois, Nevada, Oregon, Texas, and Virginia) include metakaolin, the remaining 42 states do not. Since these AMLs are also used by contractors engaged in private-sector construction, when a material is not specified on the list, it tends to limit or slow its adoption in the construction market and acts as a barrier.

Additional customer solution/market acceptance barriers are due to a lack of training and practice guidelines for ready-mix operations and concrete contractors to use limestone calcined clay types of new binders, thereby hindering its widespread use on projects. This issue was previously seen by the cement industry during the market adoption process for PLC Type-IL, where the slow acceptance over a 15- to 20-year period was driven in part by the lack of such training and practice guidelines. Contractors pushed back on the use of the PLC Type-IL product due to lack of familiarity with and understanding of how to use the product, pointing to potential barriers with respect to mix designs and rolling out appropriate solutions for construction customer applications.

Policy barriers include the lack of GHG regulation and incentives for using low-carbon cement alternatives like limestone calcined clay cement (Sree et al. 2021). The regulatory framework for cement production in the United States has not provided incentives for the scaled adoption of low-carbon cement alternatives like limestone calcined clay cement. The lack of a national or consistent nationwide carbon tax or other carbon pricing mechanisms disincentivizes companies from investing in low-carbon cement production processes, although some states are trying this approach. For example, in 2014, California established a cap-and-trade policy that covers the cement sector, leading to some emission reductions (Climate Policy Initiative 2014), and Washington State recently established a cap-and-invest program with a graduated carve out for emissions intensive trade exposed industries (EITE) through the next decade (Washington State Department of Ecology 2022). However, at the time these policies were instituted, limestone calcined clay cement was not yet being considered in the United States, and so these may not cover unique opportunities for decarbonization presented by such technologies. Also, the procurement policies of the U.S. government and other major consumers of cement have not prioritized low-carbon alternatives. This makes it difficult for companies that produce limestone calcined clay cement to compete in the market and for customers to choose low-carbon options.

This is slowly changing in the United States in the past few years with the introduction of a Buy Clean policy at the federal level and at the state level in a few states such as California, Washington, Oregon, and others (Hasanbeigi, Shi, and Khutal 2021). There have also been local-level policies and pilot projects of low-carbon concrete alternatives, such as in Marin Country, California (Marin 2022). One state, New Jersey, also introduced incentives for using low-carbon concrete in its public procurement law (the Low Embodied Carbon Concrete Leadership Act) passed in 2023 (NJ LECCLA S-287 2023). Federal agencies and other states may also follow suit based on the example offered by New Jersey.

The federal General Services Administration (GSA) just started implementing a policy mandating the use of low-carbon concrete for all its projects, signaling a significant move toward low-carbon cement and concrete. Additionally, the recent Infrastructure Investment and Jobs Act (IIJA) allocates $4 billion specifically to support the procurement of low-carbon concrete and other sustainable materials. In California, the CalGreen code has been updated to mandate reporting on the whole building's embodied carbon, setting specific thresholds that projects must adhere to. Similarly, the Leadership in Energy and Environmental Design (LEED) certification system now awards points for the use of materials with low embodied carbon, further incentivizing their adoption in the construction industry. The momentum in this sector is accelerating, and manufacturers who fail to adapt to these green building requirements risk being left behind.

Despite these developments, there may still be a **lack of awareness** and understanding of limestone calcined clay cement among policymakers, industry stakeholders, and the public. Education and outreach efforts are necessary to increase awareness of the benefits of limestone calcined clay cement and encourage its adoption in the industry.

Policy Recommendations

Testing has already demonstrated that limestone calcined clay cement concretes meet the material durability and resilience requirements of end-users. This evidence should reduce market barriers and perceived risk of their use.

However, most cement buyers and governing bodies are insufficiently informed about the many other advantages of limestone calcined clay cement.

- Clay flash calciners offer benefits such as a higher-quality product compared to some SCMs like fly ash.
- A higher mix percentage of calcined clay can be incorporated into blended cement.
- Limestone calcined clay cement has lower fuel and maintenance costs.
- Limestone calcined clay cement requires a smaller footprint and lower capital costs for a new system.

Cement buyers and governing/standard-setting bodies need to be educated about these advantages and encouraged to implement the use of limestone calcined clay cement (FLSmidth 2020). The ultimate goal is to expand the production and distribution of limestone calcined clay cements and its feedstocks.

Below we describe actions that governments, industry, and the NGO community can take to accelerate the adoption of limestone calcined clay cement in the United States.

BUILD SUPPLY BY INCREASING FINANCIAL SUPPORT

Invest in Cement Production Technology

Producers of cement and concrete should invest in limestone calcined clay cement production technology by upgrading or constructing new manufacturing facilities. Financial institutions can also provide preferable loan terms to finance the production of limestone calcined clay cement. These could raise U.S. manufacturing capacity.

Create Tax Incentives

The government should consider tax breaks for the manufacture and use of limestone calcined clay cement technology, including accelerated depreciation for limestone calcined clay cement manufacturing equipment (i.e., expensing a larger portion of asset costs in early years to reduce taxable income and tax liability and provide more short-term cash flow for a business) and tax credits for limestone calcined clay cement production.

ACCELERATE RESEARCH, TESTING, AND DEMONSTRATION

Advance Research and Development

Enhancing the workability, setting time, strength, and durability of concrete based on limestone calcined clay cement will improve the performance, viability, and compatibility of limestone calcined clay cement in various concrete mix designs. The government can finance the requisite studies, while universities and some DOE national laboratories can carry them out. NGOs can also promote more funding for limestone calcined clay cement research and development.

Conduct Performance Trials

To examine the performance of the product and pinpoint areas for development, cement and concrete makers can carry out small-scale limestone calcined clay cement studies, including accelerated testing to provide timely results. This could stimulate further industrial adoption of limestone calcined clay cement and help boost product legitimacy and market confidence in this type of low-carbon cement.

Support Pilot and Demonstration Projects

Governments and consortia of companies, structural and engineering design firms, property management firms, and other relevant entities should promote more pilot and demonstration projects, such as the MnROAD project, so a variety of scenarios may be tested, and technical and other barriers can be worked out. For example, additional northern hemisphere durability testing (i.e., in colder climates) is needed to assess properties such as freeze-thaw resistance, especially in the presence of de-icers or even salt water. More state DOTs should conduct demonstration projects (in addition to the current dozen that already have) to test out substantially reduced clinker concrete and leverage IRA funding while updating their standard specifications as they learn from these demonstration projects.

Share Success Stories

NGOs can share success stories to show the viability and advantages of employing limestone calcined clay cement in buildings and constructions. This may entail producing case studies and other materials that highlight limestone calcined clay cement initiatives and their positive effects on the environment and the economy.

PRIORITIZE POLICY AND STANDARDIZATION ACTIONS

Establish or Update Procurement and Other Policies

The GSA, which is responsible for federally owned and leased buildings and infrastructure, other agencies involved with federal procurement, and state-level procurement agencies have created procurement guidelines that emphasize the use of limestone calcined clay cement along with other sustainable building materials. Establishing or updating such policies may involve defining limestone calcined clay cement emissions reduction criteria, setting goals for the usage of limestone calcined clay cement in government construction projects, and offering incentives to contractors to use limestone calcined clay cement. Examples include federal and state Buy Clean policies and other complementary government procurement grants from DOE (e.g., support for states, local governments, and public utilities in purchasing products derived from converted carbon emissions). The goal is to speed up adoption of advanced carbon management technologies, creating a market for environmentally sustainable alternatives in building products sourced from captured emissions from industrial facilities (DOE 2023). Such policies will play an important role in advancing low-carbon solutions and can help promote the use of limestone calcined clay cement, which has lower carbon intensity than portland cement.

Existing cap-and-trade/invest policies may also need to be revisited in light of new technologies like limestone calcined clay cement, given their energy efficiency and electrification-related emissions reduction potential, though this needs to be further assessed.

Update Standards and Certification Procedures

To guarantee the quality and uniformity of the product, cement and concrete companies can offer recommendations to expand limestone calcined clay cement standards. This may include establishing or expanding limestone calcined clay cement standards and certification procedures in collaboration with regulatory authorities and standards organizations, as well as ensuring adherence to these standards. These recommendations can, for example, expand current standards (like ASTM C595) to allow for more flexibility (e.g., for limestone calcined clay cement replacement levels) and set performance requirements for low-embodied-carbon cement and concrete. Standard and certification agencies can also specify increasing amounts of limestone calcined clay cement in their existing standards for cement and concrete (e.g., increasing rates from 15% to 20%, as the latter is more technically ideal) to help promote the use of limestone calcined clay cement by providing a recognized framework for its use.

Promote the Use of Limestone Calcined Clay Cement in Building Codes and Material Specification Lists

The federal government can encourage the use of limestone calcined clay cement in public construction, and state governments can add limestone calcined clay cement and concrete to state DOT material specification lists, for example, by including limestone calcined clay cement as a permitted material or by developing distinct codes for sustainable materials for buildings and other structures.

EDUCATE THE MARKET AND POLICYMAKERS

The government, cement/concrete manufacturers, and suppliers can all educate industry professionals, customers, and stakeholders on the advantages of limestone calcined clay cement and how to use it in construction projects. This can involve offering technical assistance, training, and resources, as well as launching marketing and public relations initiatives to advance the use of limestone calcined clay cement.

NGOs can educate policymakers, business stakeholders, and end-users of cement such as architects, engineers, developers and public building owners about limestone calcined clay cement and its environmental and climate advantages. NGOs can advocate for the adoption of limestone calcined clay cement requirements at the state and federal levels; performance-based standards and specifications; laws that mandate the use of limestone calcined clay cement in public construction projects (at minimum); and subsidies and tax incentives to promote its use.

VALUE COLLABORATION AND INTEGRATION

Create Collaboration with Suppliers and Contractors

To expand the accessibility and availability of limestone calcined clay cement in the market, cement and concrete makers can create partnerships with suppliers (of construction materials and products) and contractors. This may entail collaborating with product vendors to provide a dependable supply chain, ensuring the availability of limestone calcined clay cement at the right cost, and working with contractors to promote the use of limestone calcined clay cement in their projects.

Collaborate with Governmental Organizations

Cement and concrete producers can also work with governmental organizations to create policies and guidelines that encourage the use of limestone calcined clay cement in construction. This can involve offering suggestions and criticism on proposed regulations and collaborating with government organizations such as DOE and its national labs to provide technical resources and experience.

Cooperate with Industry Stakeholders

To encourage the use of limestone calcined clay cement in the construction sector, standard-setting and certifying organizations can work together with industry stakeholders. This may involve working in collaboration with trade associations and academic institutions to create limestone calcined clay cement standards and certification programs, as well as promoting limestone calcined clay cement at trade shows and other events. Examples include the iMason Program—a group of tech companies—and ConcreteZero and the First Movers Coalition that are working to aggregate demand from leading companies for low-carbon concrete.

Work with Local Communities

To promote the use of limestone calcined clay cement in construction projects, NGOs may collaborate with local and regional communities. This may include working with neighborhood organizations and local governments to promote limestone calcined clay cement's use and spread awareness of its advantages, especially the benefits of better air quality due to reduced combustion emissions compared to portland cement plants. Examples include Marin County and its low-carbon concrete code and the City of Vancouver and the Province of Ontario in Canada, which have whole-building embodied-carbon policies. Other cities and agencies can learn from these experiences to develop their approaches.

The Path Forward

What is the path forward for limestone calcined clay cement and concrete in the U.S. market? With the unprecedented funding provided under the IRA in 2022, DOE can fund build-outs of several calcined clay production plants to not just commercialize calcined clay production facilities in the United States, but also allow exploration of electrification of flash calciners to further reduce emissions in the sector to meet 2030 and 2050 net-zero goals. Using material efficiency and energy efficiency synergistically to enable greater emissions reductions will also allow the industry to generate less new emissions and reduce the amount of carbon emissions that need to be captured and utilized or sequestered (Srinivasan and Esram 2023). Our findings in this study complement an ACEEE analysis of where to focus government and public procurement in U.S. states based on considerations such as the state policy and regulatory environment (e.g., economywide or sector-specific goals and targets), local/regional knowledge infrastructure and workforce capability, low-carbon concrete material supply, and market demand to identify states with all or many of these elements in place that are ready to go (i.e., California, New York, Texas, Colorado, Michigan, Illinois, Ohio, Florida, North Carolina, Washington), and other states with some of these elements in place that have room to grow (e.g., Georgia, Nevada, Indiana, Missouri) (Esram, Srinivasan, and Eisen 2023).

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Appendix A. Summary of Technical Details from Select International Applications

Country	Application type	Date of build/ company	Capacity	Standards met	Test results reported	Production technology
India[1]	Building: 2 story house	2014 (9 years)/Bansal Cements Ltd.	-	-	chemical, mechanical, comparison with portland cement	four types of LC3 used; blended at cement plant mill grinder
China[2]	Concrete with steel reinforcem ent	-	-	GAQSIQ & SA GB/T2419, ASTM C1362, SBQTS, MHURC JGJ55, ASTM C293	chemical, mechanical, morphology, comparison with portland cement	Trial industrial production
Brazil[3]	-	-	-	ABNT NBR7215, ISO 14067	chemical, mechanical, comparison with portland cement, LCA	six types of LC3 tested; produced at cement plant
Colombi a[4]	Commercial production of LC3	2020 ("revamped" cement plant)/ Cementos Argos	0.45 Mt/yr	-	-	Newly built rotary kiln for calcination of clay
Cuba[5]	Micro cement plant	Geominera del Central	7 t/day	-	-	-
Cuba[6]	-	-	-	ISO 14040	LCA, Cap/Opex analysis, comparison with portland cement	Wet rotary kiln, retrofitted calciner, optimized flash calciner

Country	Application type	Date of build/ company	Capacity	Standards met	Test results reported	Production technology
Cameroon[7]	Cement production plant	Scheduled commissioning in late 2021/ ThyssenKrupp	720 t/day of calcined clay; 2400 t/day cement	-	-	"Polysius activated clay" technology
Ivory Coast[7]	Cement production/ "grinding production line"	Mid-2020/CIMPOR	0.3 Mt/yr of calcined clay; 2400 t/day cement	-	-	-
Ghana[7,8,9]	Cement production plant	CBI Ghana	0.405-0.6 Mt/yr	-	-	Gas suspension calciner system, complete grinding station
France[10]	Calcined clay cement production plant	2023/Holcim	0.5 Mt/yr	-	-	Using 100% biomass fuel, waste heat recovery system

[1] Bishnoi et al. 2014
[2] Huang et al. 2020
[3] Euler, Braga, and Barata 2023
[4] LC3-Project 2020; Edwards 2020
[5] Global Cement 2019
[6] Cancio Díaz et al. 2017; Sánchez Berriel et al. 2016
[7] Perilli 2022
[8] CBI Ghana 2022
[9] Global Cement 2024
[10] Holcim 2023

Appendix B. List of Known Global Limestone Calcined Clay Production Applications

This table lists recent limestone calcined clay cement-related production projects globally.[1]

[1]Region	Country	Company, year (if available)	Type of material produced
North	United	Fortera, 2023[2]	Calcined clay blend
America	States	Ash Grove	Not specified
		Cemex	Not specified
	Mexico	Holcim	Not specified
Central	Guatemala	Cementos Progreso, 2019[3]	Limestone calcined clay
America &	Cuba	Universidad Central "Marta	cement
Caribbean		Abreu" de Las Villas, 2019[4]	Limestone calcined clay
			cement
South	Columbia	Argos Cementos, 2019[5]	Limestone calcined clay
America		Ultracem	cement
	Brazil	Ciplan Cemento	Not specified
		Vicat, 2009	Not specified
		Votorantim Group	Calcined clay blend
		Inter Cement	Not specified
	Argentina	Cementos Avellandeda	Not specified
		Votorantim Cimentos, 2019	Not specified
	Uruguay	Not available, 2024	Not specified
			Not specified
Europe	France	Holcim, 2021 and 2023[6]	Calcined clay blend
		Heidelberg Cement, 2023	Not specified
		Vicat/FLSmidth & Co. A/S, 2024[7]	Limestone calcined clay
	Denmark	Aalborg (Cementir Group), 2023	cement
	Spain	Holcim, 2023	Not specified
	Switzerland	Jura materials, 2023	Not specified
		LafargeHolcim	Not specified
	Germany	Heidelberg Cement	Not specified
	Ireland	CRH	Not specified
	Turkey	Oyak Group	Not specified
			Not specified
Africa	Nigeria	Dangote Cement	Not specified
	Angola	Nova Cimangola, 2024[8]	Limestone calcined clay
	Cameroon	Cimpor (OYAK Çimento AS),	cement
	Ghana	2023	Not specified
		CBI Ghana, 2024[9]	Limestone calcined clay
	Ivory Coast	Heidelberg Cement, 2023	cement
	South	Cimpor (OYAK Çimento AS),	Not specified
	Africa	2020[10]	Not specified

[1]Region	Country	Company, year (if available)	Type of material produced
	Tanzania	Kaolin Group, 2023[11]	Limestone calcined clay
	Egypt	Twiga Cement (Heidelberg)	Not specified
		Cemex	Not specified
	Malawi	Holcim	Not specified
		Huaxin, Shayona Cement and Cement Products Ltd, 2023[12]	Limestone calcined clay cement
Asia	India	JK Lakshimi Plant, 2016[13]	Limestone calcined clay cement
		UltraTech Cement	
		Shree Cement	Not specified
	Indonesia	SIG	Not specified
	Japan	Taiheyo Cement	Not specified
	Thailand	Siam Cement Group	Not specified
			Not specified
Middle East	Oman	Middle East Calcined Clay and Kaolin Group International[14]	Limestone calcined clay cement

[1] Source (where not otherwise identified): Scott Shell, Associate Director of Industry at ClimateWorks Foundation. 2023. Personal communication.
[2] Fortera 2023
[3] ZKG Cement 2023
[4] Cruz 2022
[5] Edwards 2020
[6] Holcim 2023
[7] Cemnet 2021
[8] Cemnet 2023
[9] CBI Ghana 2022
[10] Perilli 2022
[11] Kaolin Group 2024
[12] Perilli 2022
[13] Bishnoi et al. 2018
[14] Royal White Cement 2024

Appendix C. Additional Results and Graphs

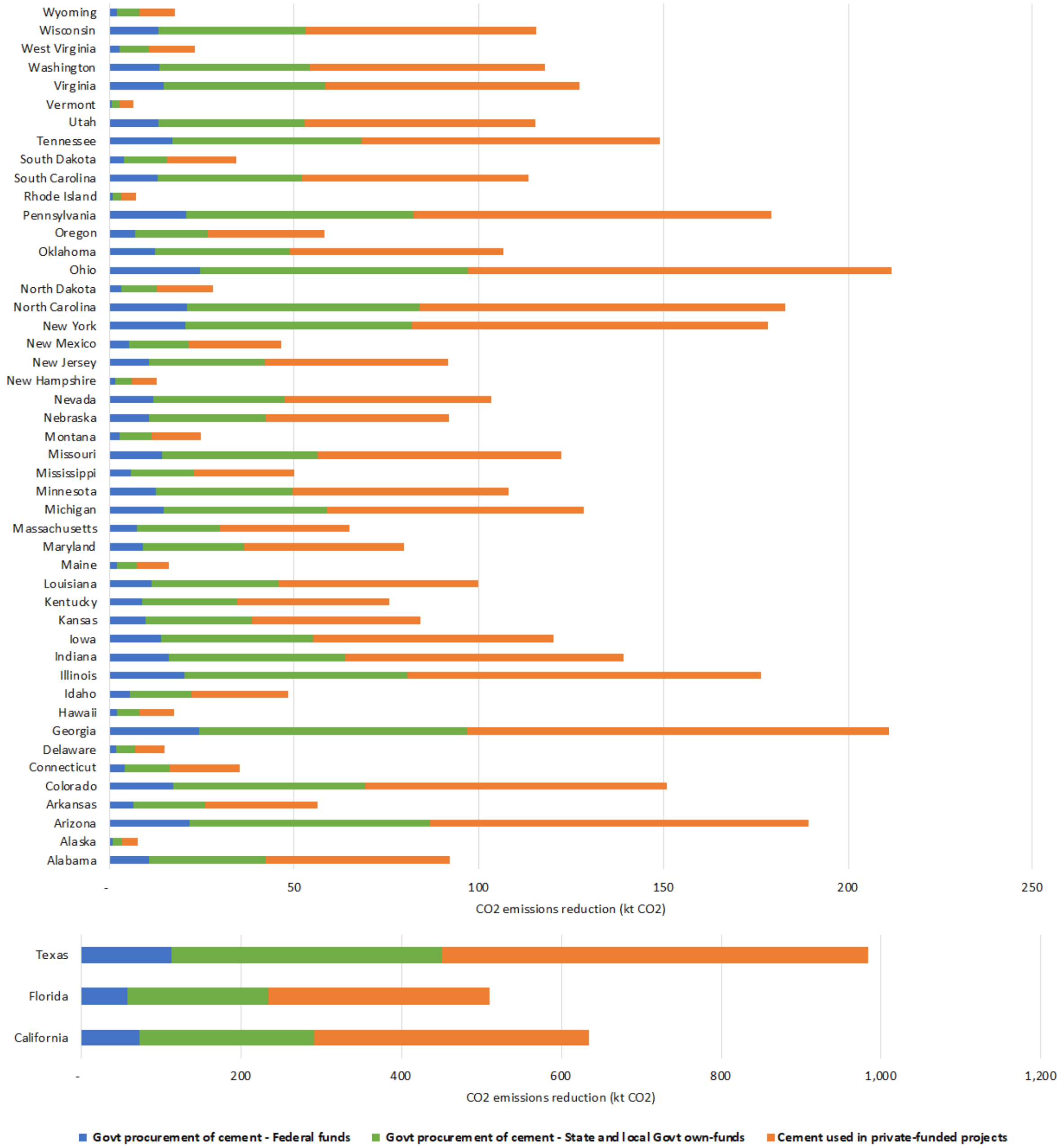

Figure A3-1. Annual CO_2 emissions reduction potential resulting from limestone calcined clay cement adoption in each state in 2021 – medium scenario (20% of cement consumption replaced with limestone calcined clay cement).

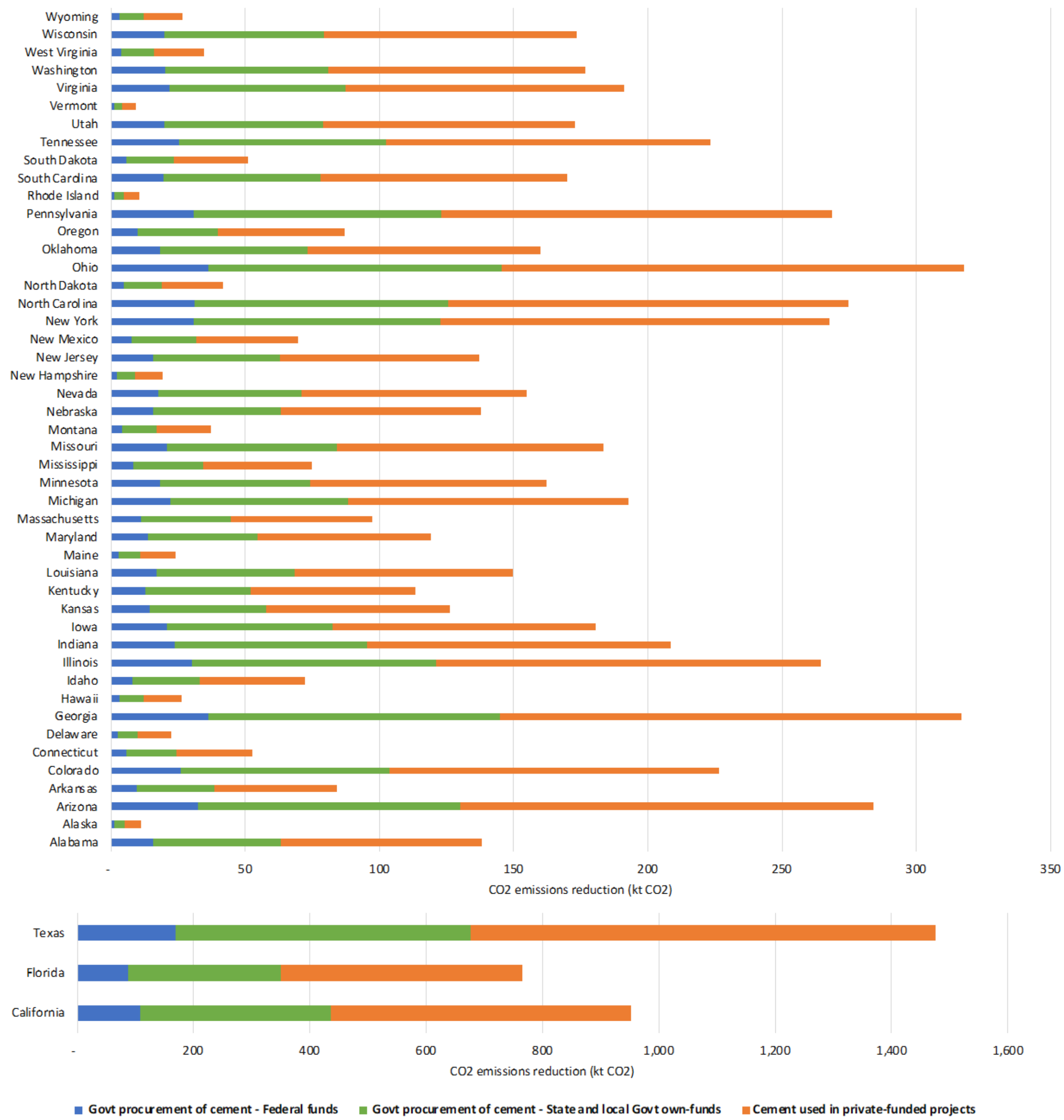

Figure A3-2. Annual CO_2 emissions reduction potential resulting from limestone calcined clay cement adoption in each state in 2021 – high scenario (30% of cement consumption replaced with limestone calcined clay cement).