NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION
SCIENCE ADVISORY BOARD

# FINAL REPORT

## LOW EMBODIED CARBON CONCRETE

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# 1 Executive Summary

Concrete production is a major contributor to global greenhouse gas emissions, accounting for 7–10% of global $CO_2$ emissions. Portland cement alone is responsible for up to 80% of concrete's carbon footprint. Although concrete typically has a lower carbon intensity per unit than many other building materials, its widespread use makes it a critical target for decarbonization. This report, developed by an Ad Hoc Committee of the Scientific Advisory Board of the New Jersey Department of Environmental Protection (NJDEP), provides a comprehensive overview of low-carbon concrete (LCC) technologies, policies, and implementation strategies relevant to New Jersey.

Sources of Emissions in Cement Production: The report identifies three main sources of emissions in cement production- the combustion of fuels to heat kilns, the energy required for raw material processing and transport, and the calcination of limestone, which releases $CO_2$ as a byproduct. While technological improvements such as kiln efficiency and alternative fuels have been implemented, overall emissions continue to rise due to increasing global demand for cement. In New Jersey, where there are no cement manufacturers but approximately 350 concrete producers, the challenge lies in identifying practical, scalable, and economically viable solutions for reducing emissions at the point of concrete production.

Policy Framework and Benchmark: The report explores the policy landscape through examples from California, New York, and Washington, where Buy Clean legislation and global warming potential (GWP) thresholds have been implemented. New Jersey's own low-carbon concrete legislation places responsibility on the concrete industry to meet emissions reduction targets. The report recommends adopting ACI Code 323-24 as the standard for defining and certifying low-carbon concrete, using a 15% reduction from regional benchmarks as the threshold. Preliminary benchmarks based on New Jersey Department of Transportation (NJDOT) data and the National Ready Mixed Concrete Association (NRMCA)/Athena Institute's Northeast regional averages are proposed. However, these benchmarks are preliminary, and it may not be comprehensive enough for statewide application due to limitations in the data set and range of strengths, as well as reliance on NJDOT-specific concrete classes. Therefore, these values should be continuously improved by collection of more localized data over time.

Potential Low-Carbon Concrete Technologies: A range of low-carbon concrete (LCC) strategies is evaluated in the report, including the use of supplementary cementitious materials (SCMs) like fly ash and slag, optimization of aggregate gradation, incorporation of recycled aggregates, and the use of alternative binders such as calcium sulfoaluminate cements and geopolymers. The report also discusses emerging technologies that incorporate $CO_2$ directly into concrete through mineralization or carbonation curing, though these approaches face challenges related to $CO_2$ sourcing, cost, and scalability. Additionally, the report highlights the importance of reducing overdesign in concrete mixtures and adopting performance-based specifications to minimize unnecessary cement use.

Certification: Environmental Product Declarations (EPDs) are identified as the preferred method for verifying the global warming potential (GWP) of concrete mixtures. Where EPDs are not available, third-party life cycle assessments or prescriptive limits on cement content may be used. The report concludes with a set of recommendations for NJDEP, including the adoption of ACI Code 323-24, the establishment of preliminary GWP benchmarks, and the development of a process for collecting and analyzing local concrete data to support ongoing emissions reductions.

In summary, this report provides a detailed roadmap for implementing low-carbon concrete practices in New Jersey. It outlines the technological, regulatory, and market-based tools available to reduce emissions from concrete production and offers practical guidance for setting thresholds and verifying compliance. By adopting these strategies, New Jersey can position itself as a leader in sustainable construction while supporting the concrete industry’s transition to a low-carbon future.

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# 2 Charge Question

The impetus for this report was a charge question for the Science Advisory Board posed by the Air, Energy and Materials Sustainability program of the DEP, specifically the Division of Climate, Clean Energy, and Radiation Protection, in July 2023. This charge was related to bill S287 (2022-2023 legislative session), which Governor Murphy signed on January 30, 2023, revising § 13:1D-70 and § C.54:10A-5.49. The text of the law defines the scope of carbon emissions but leaves it up to the Department to define the threshold for "low embodied carbon concrete" and the methods for certification. The Department is seeking assistance in identifying certification methods and defining "low embodied carbon concrete" so that the maximum reduction in concrete-related carbon emissions is achieved by 2050. "Low embodied carbon concrete" is defined in the law (S287) at https://pub.njleg.state.nj.us/Bills/2022/PL23/4_.PDF

Specifically, DEP asked the SAB to:

1. Determine a baseline of carbon emissions resulting from concrete and Portland cement use in New Jersey.

2. Identify what "low embodied carbon concrete" products are currently on the market or are expected on the market in the near-term, including their availability in New Jersey.
    a. Identify what likely advancements in concrete are predicted between now and 2050.
    b. Document the methods and reliability of certifying concrete as "low embodied carbon concrete".

3. Determine an estimate of carbon emissions that could be avoided by switching to low-carbon concrete in New Jersey between now and 2050, including the limited funds available for these tax incentives.
    a. Identify a range of possible thresholds for defining "low embodied carbon concrete" concrete, such as 25%, 50%, etc. reduction of carbon emissions, based on the products determined under 1.b. of S287. These thresholds could be static or dynamic.

4. Recommend threshold(s) and certification methods to use to ensure the department's review is meaningful and certification is offered consistently. This recommendation should incorporate lessons from other locales with similar policies and seek to maximize environmental, economic, and social benefits.

# 3 Introduction

Concrete production is responsible for 7 to 10% of the world's $CO_2$ emissions. Traditional concrete is composed of hydrated portland cement, gravel, and sand. The gravel and sand are collectively referred to as aggregate. Cement makes up about 15% of concrete and has a carbon intensity per unit (CIPU) approximately 20 times that of gravel and sand; it is responsible for approximately 80% of concrete's $CO_2$ emissions (Flower and Sanjayan, 2007). Intergovernmental Panel on Climate Change (IPCC, 2022) reports identify cement production as the largest industrial $CO_2$ emitter of all industrial chemicals. Concrete production has a lower CIPU than other building materials (Miller, Horvath, and Monteiro 2016; Miller 2020). The CIPU is frequently called the carbon footprint, where a positive number is the net amount of $CO_2$ generated from all the raw materials, process steps, and transportation required to deliver and install the product for its intended application. For example, steel produced by a basic oxygen furnace has a carbon footprint of ~2 metric tonnes-$CO_2$ per metric tonne of product (World Steel Association, 2024), while that of portland cement hovers around 0.9 (USEPA, 2021). The carbon footprint of portland cement output results from more than 4.3 billion tonnes being produced annually (Lehne & Preston, 2018). While portland cement is used in a broad range of applications beyond concrete, over 14 billion cubic meters of traditional concrete are cast each year (GCCA, 2025). Because concrete is used at such a large scale, it represents a key opportunity for significant carbon footprint reduction.

Carbon emissions from cement production come from three primary sources. First, carbon is emitted because of burning fuel to achieve the 1450˚C temperature in the kiln required for the limestone to calcium oxide decomposition and to react calcium oxide with silica to form two calcium silicate phases that react with water to harden concrete. Second, carbon emissions are associated with the energy required to mine raw materials, crush, and transport the materials. And third, the decomposition of limestone into calcium oxide results in the release of $CO_2$, a process known as calcination. Heating of the kiln accounts for roughly 40% of the associated carbon emissions and calcination accounts for around 50% of the associated carbon emissions (Lehne & Preston, 2018). Significant efforts within the cement industry have been made to lower the emissions associated with cement production, including improvements in cement kiln efficiency, collecting and sequestering the $CO_2$ emissions at the plant, and using non-fossil fuels to heat the kiln (Thomas Harrison, Martyn Roderick Jones 2019; CSA 2009; L. Barcelo, J. Kline, G. Walenta 2014; Rosen 2020). Methods that have been successful and economical have already seen widespread application at plants within the US. However, these methods have not effectively reduced overall $CO_2$ emissions within the US or abroad, in part because increased emissions from cement production growth have far exceeded any savings from existing production changes. Other efforts remain in a research and development mode, or they involve using specialty raw materials available only in quantities that cannot support the concrete supply chain's enormous quantities or distributed nature. Up to now, the responsibility for solving this problem has been incumbent on the cement industry. Still, more recently, individual states have created legislation that places the commitment to reduce carbon emissions primarily on the concrete industry. This is relevant in New Jersey, where there are no cement manufacturers but approximately 350 concrete manufacturers. The concrete industry needs practical solutions that reduce $CO_2$ and are economically feasible.

This report was developed to describe the current state of low-carbon concrete policy, technology, and implementation, as well as guide how recently enacted low-carbon concrete policies may be implemented in the State of New Jersey. The following sections provide pertinent background information and were compiled through an Ad Hoc Committee of the Science Advisory Board of the New Jersey Department of Environmental Protection. The report concludes with recommendations for DEP that specify thresholds and certification methods.

# 4 Embodied Carbon of Concrete

The embodied carbon of concrete mixtures can vary widely, depending on the materials used and the method used to calculate the emissions. The most common method for determining the embodied carbon of concrete is using an Environmental Product Declaration (EPD). An EPD is an "ISO (International Organization for Standardization) type III Environmental Declaration" that meets the requirements of ISO 14025 (EPD International 2024). An EPD requires third-party verification and, within product categories, can provide comparable environmental impact data. Product category rules (PCRs) set the rules for the Life Cycle Assessment (LCA) that EPDs must meet within a given material category (EPD International 2024). The current PCR for ready-mix concrete examines only the upfront, cradle-to-gate emissions associated with a concrete mixture. Cradle-to-gate emissions include raw materials extraction for all ingredients, process steps to make the cement and aggregate, and concrete batching at the ready-mix concrete plant. The end gate for the current system occurs when the concrete leaves the ready-mix facility, so it does not include transportation of the concrete to the construction site or the emissions associated with placing and finishing the concrete (NSF 1112-19 2024).

The entire lifecycle or whole-building emissions of concrete construction include the upfront emissions (manufacturing and construction process stages) and the use and end-of-life stages. Currently, EPDs only account for manufacturing stage, or cradle-to-gate emissions.

While whole-building/whole-lifecycle analysis can be conducted following ISO standards, there are no associated rules, similar to those set forth in PCRs, for performing such analyses for a product from cradle to grave. Thus, fully valid comparisons of various concrete products will only be meaningful once appropriate tools are developed to standardize the process.

## 4.1 Overview of Current Policies on Low-Carbon Concrete

Various low-carbon concrete policies have been implemented or proposed throughout the United States. California, New York, and Washington have been some of the leaders in implementing low-carbon concrete policies through legislation and codes.

One of the earliest policies for limiting concrete's global warming potential (GWP) was developed in Marin County, CA. This policy applies to concrete placements larger than 50 cubic yards within the unincorporated areas of Marin County. It requires that the concrete either meet a GWP limit or limit the amount of portland cement per cubic yard in the concrete mixture. The limits were devised through a comprehensive study of local concrete mixtures to determine what was feasible in the area (Cardno 2020).

In California, a statewide Buy Clean California program for concrete was put into place through Bill AB-1356, which requires concrete producers to submit EPDs for eligible state projects, involves the specification of a GWP performance standard, the establishment of a benchmark for concrete GWP, and a 5% bid discount for proposals using low-carbon concrete (Craig 2021). CalTrans, the California state transportation agency, has also initiated a program for low-carbon concrete that requires the reporting of EPDs for concrete purchased for all DOT projects (Butt and Harvey 2021). Colorado has also undertaken a Buy Clean Act, similar to what was enacted in California. Concrete and other building materials are examined via GWP standards every four years (Colorado OSA 2024). Washington state, Maryland, and Massachusetts have also passed similar legislation. The main variation in these laws is which agency is required to manage the program, and which products are covered under the law; concrete is covered in all locations.

The Low Embodied Carbon Leadership Act and Buy Clean legislation in New York have led to setting GWP threshold requirements for concrete and other building materials. New York requires the submission of EPDs for state-funded projects and requires the GWP of concrete materials to be under 150% of the National Ready Mixed Concrete Association (NRMCA) benchmarks. These requirements apply only to contracts exceeding 1 million dollars and using at least 50 cubic yards of concrete. They also allow an exemption for concrete that requires high early strength or where meeting the requirements is not feasible due to access to materials. The state expects to lower the threshold for GWP for concrete mixtures periodically (New York State Office of General Services 2024; NYS Department of Environmental Conservation 2024).

Washington state has also legislated that the state building code must consider language addressing embodied carbon within the building code. Washington state is the first location to consider carbon emission limits in the building code, but no final decision has been made at the time of this report (Washington State Legislature, 2024).

## 4.2 Low embodied carbon concrete products and technologies

The potential technologies that can be used for low-carbon concrete design, not considering technologies reducing emissions at the cement plant, can be broken into six main categories:

1. Use of supplementary cementitious materials (SCMs);
2. Reduction of total cementitious materials content through improved aggregate gradation and filler materials;
3. Use of lower carbon non-portland hydraulic cements in targeted applications;
4. Incorporation of mineralized $CO_2$ into concrete mixtures as a sequestration method;
5. Use of recycled aggregates;
6. Structural design considerations for reducing the total amount of concrete.

The following section will discuss the basic technical information required to understand these technologies and their implications for concrete mixture design, strength, and durability.

### 4.2.1 Supplementary Cementitious Materials

SCMs have been used successfully for many years to improve long-term strength and durability. SCMs are important because their addition reduces the amount of portland cement required for a concrete formulation. SCMs can be derived from minerals (e.g., volcanic ash), synthetic (e.g., carbonated slag, carbonated wollastonite mineral, calcined clay), and waste products (e.g., slag, fly ash). SCMs can modify the cement hydration process in two ways. First, pozzolanic activity occurs when the SCM reacts with calcium hydroxide to form a calcium silicate hydrate. Second, hydraulic activity occurs when the SCMs contain compounds that react directly with water to form a hydrate. The balance of pozzolanic versus hydraulic activity depends on the SCM's chemical and physical characteristics. SCM addition requires cement or concrete formulators to optimize their concentration and processing methods to obtain acceptable strength and durability, and when used inappropriately can result in a shorter service life than desired (Wilson and Tennis 2017). While SCMs provide a means to reduce the carbon footprint, their large variations in chemical and physical characteristics require ongoing optimization of concrete mixtures. More importantly, the large variety of SCMs, the limited supply chain, and their variation from region to region create a challenge to ensuring all concrete formulations meet the performance standards for the concrete industry. While the specific SCMs may be new, concrete has always been an engineered product, created using a variety of materials in varying amounts tailored to meet the needs of the project. The industry is capable of this level of ongoing adaptation as it is currently accustomed to constantly adapting to changing aggregates, cement compositions, SCM compositions, and construction and durability requirements.

SCM substitution for portland cement reduces the carbon footprint of the concrete formulation. Some SCMs, such as slag cement, fly ash, and glass pozzolan are produced as a by-product of other economic activities; other SCMs are directly produced from raw materials, such as calcined clays or metakaolin. Reduction in carbon emissions when using SCM can vary because the amount of portland cement replaced by an SCM depends on the performance requirements of the concrete and the particular SCM. Methods for accounting the carbon emissions associated with an SCM are not standardized, and some SCMs can result in rapid carbonation (Thomas Harrison, Martyn Roderick Jones 2019; 16970 2015; CSN EN 15804+A2, n.d.; Brinkman and Miller 2021; Miller 2018). Carbonation is the process through which $CO_2$ reacts with the calcium hydroxide in concrete to form $CaCO_3$ chemically binding the $CO_2$.

Traditionally, SCMs produced from by-products of industrial processes have been considered to have zero carbon emissions. As EPDs have become more prevalent, allocation of carbon emissions to SCM production and transportation has changed. The current PCR for concrete recognizes fly ash, slag, and silica fume as recovered materials, not co-products. Therefore, emissions associated with treatment and transportation to use the SCM in concrete are accounted for, but emissions associated with the industrial process that created the waste material are not considered (NSF 1112-19 2024). Alternatively, it has been suggested that a portion of the overall $CO_2$ emissions of the main product to the be attributed to the SCM if the material is a source of income (H Wang et al. 2022). For example, a portion of the $CO_2$ emissions associated with steelmaking could be assigned to the slag produced, resulting in a positive carbon emission associated with the SCM. This viewpoint assumes that incorporating waste products from extensive carbon-emitting processes is an incentive to continue manufacturing highly carbon-positive products such as steel instead of developing a low-carbon-emitting process. This consideration has not been incorporated into GWP calculations used for EPD, however.

Despite the concern that encouraging the use of fly ash and slag may encourage continued construction of coal burning facilities, there is a large volume of legacy waste produced over the last 100 years that is currently stored in landfills. One example is legacy ash produced by the Tennessee Valley Authority (TVA), which has generated tens of millions of tonnes from coal-burning power plants. Research has shown that recovered fly ash materials from landfills can work well as an SCM, and the legacy waste materials are currently being sold and used in concrete (Hooton & Thomas, 2021; EPRI, 2021). There is an ongoing debate as to whether encouraging the use of these legacy materials will encourage the ongoing burning of coal and traditional methods of steelmaking. However, given the limited supply of alternative SCMs that are not by-products of coal burning or steel making currently available on the market in the United States, there are not yet other options that can fulfill the amount of material needed to sustain the current construction market. There is also a challenge in using waste materials as there is considerable variation in chemical and physical characteristics.

#### *4.2.1.1 Blended Cement*

Pre-blended cement systems are becoming more common as the need for low-carbon cement systems has increased. A pre-blended system is a mixture of portland cement and filler material such as ground limestone or an SCM such as slag (Wilson and Tennis 2017). It is formulated at the cement plant and delivered to a concrete production facility. Pre-blended systems can help increase consistency, as they are designed to perform consistently between deliveries from the same source.

#### *4.2.1.2 Aggregate Optimization*

The total amount of binder used in a concrete mixture can be reduced by optimizing aggregate contents in the system. Several studies have shown that a reduction in embodied carbon can be produced while maintaining performance quality by considering particle packing models for aggregates with low-binder concrete (Moini et al. 2015; Adams et al., 2024). This work showed that cuts in cement contents up to 18% have been achieved through this design technique without impacting strength, effectively reducing the system's carbon footprint by a similar amount since cement is the major contributor to $CO_2$ in concrete. The total reduction capability is highly dependent on local aggregate sources; however, it requires significant analysis and testing, which can increase concrete prices in the short term.

### 4.2.2 Filler Materials

Similar to improving particle packing through optimizing aggregate gradation, particle packing can also be improved by using filler material. One of the more common materials used in this way is finely ground limestone, which has limited reactivity in concrete but can be used at replacement levels up to 15% with minimal impacts on performance. Cement made with ground limestone is being sold as Type 1L, per ASTM C595, or portland-limestone cement (PLC). In some parts of the country, it is now the leading cement available for concrete producers (ASTM C595/C595M-21 2022; Bonavetti et al. 2003; 1999).

### 4.2.3 Alternative Non-Portland Cements

Several common non-portland hydraulic cements are currently used worldwide. Hydraulic cement is defined by its ability to harden and set when it comes in contact with water. Two of the most used non-portland hydraulilc cements include calcium sulfoaluminate (CSA) cement and calcium aluminate cement (CAC). CSA and CAC are both pyroprocessed using equipment similar to what is used for ordinary portland cement (OPC). However, their carbon emissions profiles differ significantly due to variations in raw materials and processing conditions. CSA emits about 34% less $CO_2$ than OPC, primarily due to its lower limestone content and reduced calcination temperatures (Zhang et al., 2025). This makes CSA a promising low-carbon alternative in applications where its rapid setting and high early strength are advantageous. The emissions profile of CAC is more complex. Some studies (e.g., Kumar, 2022) report that CAC used in concrete applications has comparable $CO_2$ emissions to OPC, however recent research suggests that certain CAC formulations may offer lower emissions, particularly at the kiln stage (Baloch et al., 2025). Despite their benefits, the broader adoption of CACs faces challenges. The conversion of metastable hydrates over time can compromise long-term strength. Additionally, production costs are elevated due to the limited availability of bauxite, the primary source of alumina. The rapid setting behavior of CAC mixtures can also hinder in-situ casting operations, while their inherent brittleness and low tensile strength restrict their use in structural applications requiring ductility (Juenger et al., 2011b). Moreover, CAC requires more energy-intensive grinding and often higher cement content to maintain strength after conversion, which can offset some of the kiln emission benefits (Adams & Ideker, 2017).

CSA cements, despite having a lower embodied carbon compared to portland cement are generally not an appropriate cement for replacement of portland cement in all concrete activities. CSA is very useful for situations where rapid repair of concrete systems is required, or rapid construction is required because it can set and gain strength rapidly (Juenger et al. 2011a). Although CAC systems gain strength rapidly, they undergo a process known as conversion, where significant strength is lost due to a delayed reaction that results in porosity formation in the concrete (Adams & Ideker, 2017). While the converted strength can be predicted, several high-profile failures in the 1970s resulted in limited use of CAC for structural applications (Adams, 2015).

Geopolymer systems, also known as alkali-activated cementitious materials, gain strength through a chemical reaction between an alkaline activator material (e.g., sodium or potassium hydroxide) and an aluminosilicate-rich material such as fly ash or slag (Provis 2018). These systems also require no cement content. However, this advantage is heavily offset by using an alkaline activator, whose carbon footprint can be as high as 3.5 t-CO2/t-NaOH, because alkaline activators are manufactured electrochemically, creating harmful chlorine gas as a by-product. The inefficiencies of the electrochemical process make most geopolymer formulations more carbon-positive than portland cement. Research focused on vastly reducing the amount of activator indicates it is possible to create cement with a lower carbon footprint than portland cement. However, these new low-$CO_2$ emission formulations have not been demonstrated to meet the standards for infrastructure use. More importantly, the production of activators is neither well distributed nor of sufficient magnitude to supply the concrete market (NaOH production ~140 Mt/y)( McLellan et al., 2011; Rincon et al., 2023). Increased production will create an excess of chlorine gas, an environmental hazard if not sold and utilized. Geopolymer cements are also quite difficult to utilize in the field, given the need for hazardous chemical activators. They also typically have different workability and set times which, while surmountable, result in a high barrier to application for most construction applications. Therefore, geopolymer cements are not currently viable for portland cement replacement.

### 4.2.4 Novel Cement Production Technologies

The inherent problems with non-portland cement have accelerated the development of many new technologies. These technologies are based on hydraulic cement, carbonate cement, or a hybrid of hydraulic and carbonate cements.

Many startup companies have been founded based on hydraulic cement. Brimstone makes conventional portland cement via a novel process using calcium aluminosilicates that consumes less energy. However, their process involves high pressures and uses large amounts of sulfuric acid (Finke and Leandri, 2021). Batuga Tech (Batugatech, 2025) uses a process that avoids using limestone and a conventional pyrothermal cement mill to make portland cement, resulting in less $CO_2$ emissions. However, the process also generates SOx or sulfuric acid, which must be disposed of or utilized. Sublime's technology is a limestone-free electrochemical process requiring almost twice the energy needed to make portland cement.

Another technology avoids the need for a cement mill altogether. For example, Ecomaterial (Eco Material Technologies, 2024) uses mechanochemistry to treat ash and slag so it can be cured by hydraulic means. The technology creates a low-carbon footprint cement without using portland cement. Even if the variation of chemical and physical characteristics of these raw materials is inconsequential to this process, the limited supply of slag and ash and its poor supply chain distribution throughout the US limits its practical utility. C-Crete creates concrete with low carbon emissions. They claim to use no cement in their formulation but fail to mention what is added to induce hydraulic activity.

Solidia Technologies was one of the first startup companies to propose using a new cement called monocalcium silicate, which cannot hydrate but can solidify concrete by introducing $CO_2$. Monocalcium silicate can be produced at a lower temperature and with less limestone than portland cement. Using this lower carbon footprint cement and using $CO_2$ to solidify can reduce emissions relative to portland cement by as much as 70% (Anderson & Duxson, 2019; Solidia Technologies, 2019).

More importantly, these companies do not include the carbon footprint of $CO_2$ in their analysis, which can vary from 5-50% depending on how it is manufactured, stored, and transported (Barcelo et al., 2014). Another deficiency for carbonate cements lies in its requirement of $CO_2$ as a feedstock. Capture of $CO_2$ generally occurs from the separation of flue gases, although it can also be extracted through direct air capture or recovered from gases released during fermentation. In total, $CO_2$ world production is at least ten times less than required if all concrete output were based on carbonate cement. If a highway is constructed with this type of cement tomorrow, approximately 26 $CO_2$ trucks will be needed to pave a mile of 4-lane road. $CO_2$ companies have far fewer trucks in a single location. Furthermore, the distribution of $CO_2$ is not uniform. Many states in the US lack $CO_2$ production. Thus, transport over long distances over 200 miles can make $CO_2$ prohibitively expensive.

### 4.2.5 Alternative and recycled aggregates

Aggregates comprise a substantial portion (60-75%) of total concrete volume, which can cause a significant demand for natural resources because they are mined directly from the earth for each new application of concrete (Adams et al. 2016). The total volume of aggregates produced yearly also results in substantial $CO_2$ production, if much lower than that of portland cement. Therefore, utilizing alternative and lower embodied carbon aggregate systems can improve the overall sustainability of concrete. Recycled concrete aggregates (RCA), produced from demolished or unused concrete, are viable alternatives to using natural aggregates in concrete. Concrete with good quality strengths can be made using RCA (Jayasuriya et al. 2021), and typically, good durability performance is found in concrete containing RCA if specific design considerations are considered (Ideker et al. 2013). RCA is beneficial in drying conditions, reducing the likelihood of cracking in concrete undergoing shrinkage (Adams et al., 2016). Using RCA concrete can reduce the emissions due to aggregate production and transportation. However, this typically depends on the distance the material is transported from the demolition site to the recycling facility and then to the concrete facility. The carbon footprint reduction is often minimal if that is more than the distance for the natural aggregates (Adams 2013). Due to the relatively low impact of emissions of aggregates associated with an individual concrete mixture, aggregate sustainability has not been a focus of design changes in concrete when compared to studies examining replacement and reduction of portland cement.

Recycled concrete is one promising option for New Jersey to reduce $CO_2$ emissions. There are approximately 350 concrete companies in New Jersey (POI Data, 2025) that could use recycled sources from within the state rather than bringing cement in from out-of-state. This would provide a long-term solution for concrete carbon footprint reduction. Between NJ and NY, there are hundreds of concrete recyclers and demolition companies that can supply concrete rubble on the scale of millions of tonnes per year. By carbonating recycled cement and using it as an SCM, manufacturers could reduce the carbon emissions of their concrete mixes.

There are a few barriers to this concept. The first is the need for a scaled-up method for separating the cement. The system to sort, process, and carbonate the recycled concrete would need to be developed incrementally on a state scale over the coming years. The second barrier is a low-cost carbonation process. The third is a supply chain for $CO_2$ that can supply millions of tonnes of $CO_2$. Rutgers University is currently working on solutions to the first two barriers (Ellis et al., 2023). Regarding the third barrier, $CO_2$ plants are expensive to build, costing $400M/plant (De Luna, 2025; Guleria & Goyal, 2025). Many states in the US do not have $CO_2$ plants. In addition, the processing of $CO_2$ requires energy to purify the gas, and its sources need to be nearby. However, using recycled cement to capture $CO_2$ directly from the air is possible.

Materials that permanently store $CO_2$ can generate revenue through carbon offsets and federal tax incentives. For example, constructing a mile of roadway can embed approximately 750 tonnes of $CO_2$, which could be monetized if entities such as tech companies purchase the associated offsets. This approach offers a potential mechanism to reduce the net cost of infrastructure projects. However, most carbon prices globally remain below $160 per tonne, with only about 3.2% of emissions priced at levels aligned with Paris Agreement targets (typically $160–$200/t$CO_2$e or higher) (World Bank, 2025). This suggests that while carbon offset markets offer potential, their current pricing may not fully support large-scale investment without additional incentives. In the U.S., the Section 45Q tax credit provides an additional incentive: entities that store $CO_2$ in products may claim $85 per tonne, provided they store at least 12,500 tonnes per year for equipment placed in service after December 31, 2022, and construction beginning before January 1, 2033 (Jones & Marples, 2023).

### 4.2.6 Reducing overdesign of concrete

Excessive overdesign of concrete mixtures contributes significantly to the embodied carbon of the built environment; this refers to using an excess amount of concrete compared to what is necessary for a reasonable safety factor in the built environment. Overdesign can result from a desire to speed up construction by increasing cement content to increase early strengths, low-quality testing capabilities resulting in incorrect strength results during quality assurance testing, and excessive risk aversion during the design process. A recent study indicated that overdesign may be responsible for 6.7% of portland cement overuse within the construction industry (Buffenbarger et al., 2023). Methods to reduce overdesign include using performance specifications rather than prescriptive specifications, improving construction practices, and better education and training of testing laboratories.

### 4.2.7 Availability of Materials and Technologies Nationally and in New Jersey

Within the United States, availability of SCMs, portland cement, portland limestone cement, and other technology can vary drastically depending on geographic location. In general, though, portland cement, portland limestone cement, fly ash, and slag can be obtained in all regions. Slag tends to be more prevalent in some regions (northeast, southwest, midwest) with fly ash being prevalent in others (southeast, appalachia, mountain-west, and pacific coast) depending on the location of coal-burning plants, steel production facilities, and ports that are importing products such as slag and ash from overseas. Other SCMs such as ground glass pozzolan are only available within certain local regions, depending on where production facilities have been built.

In New Jersey, PLCs are generally available, though some companies import them from other countries since they do not yet have production capabilities within the US. Emissions from transit are likely offsetting the carbon savings provided by replacing a portion of the cement with ground limestone. Both fly ash and slag are available but slag is more widely used. Ground glass pozzolan, an SCM, is available throughout New Jersey, and there is also a regional production facility owned by Urban Mining Industries in western Connecticut. Some of the specialty products noted in Section 3.5 are available within NJ, but require project-specific purchases, rather than existing as readily available off-the-shelf mixtures. These products generally come with a significant cost barrier.

Other tools such as designing for durability, reducing overdesign, optimizing aggregate content, and using performance specifications rely on engineering analysis and decisions rather than specific material availability. Therefore, while these tools are generally available within the region, engineers, producers, and contractors who are knowledgeable in design and implementation of the technologies are necessary. These techniques are not necessarily baseline knowledge for all structural engineers and therefore can come with a cost increase.

## 4.3 Baseline of carbon emissions in New Jersey

Currently, no New Jersey-specific baseline for carbon emissions from concrete exists. Recent efforts to create viable benchmarks worldwide have been hindered by government agencies' lack of data availability and no requirements for concrete material tracking. The most comprehensive benchmark for carbon emissions associated with publicly available data was published by the Athena Institute in collaboration with the National Ready-Mixed Concrete Association (Athena Sustainable Materials Institute 2022). While this report provides some valid benchmarking data, it should be noted that it also has limitations:

- The data is based on volunteered information from participating ready-mix facilities, so it may not represent a realistic average across all facilities.
- The data only provides benchmarking information for normal-weight and light-weight ready-mix concrete ranging from 2500 to 8000 psi.
- Regional averages are based on an average mixture design, not average emissions values. Thus, a mixture design using average supplementary cementitious materials to portland cement ratios, water-to-cement ratios, and aggregate amounts was used

to calculate the average GWP for a region rather than an average GWP from all EPDs submitted within an area.

- The data assumes that classification by compressive strength is the best indicator of GWP, but recent research has indicated a weak positive correlation.

The national and regional benchmark GWP reported by the report (Athena Sustainable Materials Institute 2022) are presented below in Table 1.

*Table 1: Benchmark GWP Values (per cubic yard)*

| **Strength (psi @ 28 days)** | **2500** | **3000** | **4000** | **5000** | **6000** | **8000** | **3000LW** | **4000LW** | **5000LW** |
|---|---|---|---|---|---|---|---|---|---|
| **National Average GWP (kg $CO_{2e}/yd^3$)** | 183.49 | 200.57 | 235.61 | 278.99 | 294.57 | 341.31 | 376.42 | 412.94 | 449.77 |
| **Northeast Regional Average GWP (kg $CO_{2e}/yd^3$)** | 183.29 | 201.48 | 240.22 | 289.03 | 305.26 | 360.51 | 395.35 | 437.90 | 480.10 |

The total emissions presented in Table 1 represent the upfront embodied emissions associated with the production of ready-mix concrete, including the raw material supply, transport, and manufacturing of the concrete, but not the transportation of the concrete to the project site nor the construction and installation of the concrete (Athena Sustainable Materials Institute 2022).

## 4.4 Tentative benchmark from available New Jersey data

Data is not available for all concrete usage in New Jersey, but there is some information available for the transportation sector. To set a tentative benchmark, we determined the carbon footprint for the concrete mixtures provided by the New Jersey Department of Transportation (NJDOT). Thirty-three mixtures used by suppliers to NJDOT were included across five classes: P (6), AL (A, Lightweight, 5), A (6), B (7), and HPC (9). These suppliers were primarily based in NJ, with a few in PA, MD, and NY. The concrete classifications are defined as follows:

- Class P: Precast concrete with a design strength of 5500 psi, and no specific requirement for water-to-cement ratio or water content.
- Class A: Ready-mixed concrete with a design strength of 4600 psi, a water-to-cement ratio of 0.443 and 5 gals of water per bag of cement.
- Class AL: Ready-mixed concrete with the same requirements as Class A, except using lightweight aggregates, which typically have a higher embodied carbon.
- Class B: Ready-mixed concrete with a design strength of 3700 psi, a water-to-cement ratio of 0.488 and 5.5 gals of water per bag of cement.
- Class HPC: Ready-mixed concrete with a design strength of 5600 psi, a maximum water-to-cement ratio of 0.40, and allows the use of SCMs.

Determination of the carbon footprint followed the general guidance of ISO 14044 and included the production stage (A1 extraction and upstream production, A2 transportation to factory, and A3 manufacturing). IPCC 2013 (AR5) was used as the impact assessment method, and 100-year global warming potential (GWP100) was used as the life cycle impact indicator to represent the carbon footprint. Mix data from NJDOT was combined with corresponding GWP100 values to determine the impact contribution for each component. As cement was the dominant contributor to the overall GWP100, we used vendor/plant-specific data if EPD was available with a total GWP100 available for the cement. If no EPDs were available from the vendor, we used the industry average data for the specific class the Portland Cement Association reported. The industry average GWP100 for slag was used for most of the mixes, except for a few vendors for whom EPDs were available.

Additionally, for slag, fly ash, and silica fume that were waste or by-products from other processes, only environmental impacts associated with the treatment and transportation required to use an SCM were included. For admixtures including air entrained, set accelerator, plasticizer, water reducer, and retarder, LCI data from the OpenConcrete calculator (Kim et al., 2022) was used (assuming the US average electricity mix). For corrosion inhibitors without LCI data, a 30% calcium nitrite solution was used based on the manufacturer datasheets. Transportation of cement, slag, fly ash, silica fume, and aggregates was calculated based on the distance between the supplier and the concrete plant, assuming truck transportation. Transportation of admixtures was excluded due to their small quantities compared to other components. Finally, impacts for batching were included based on the LCI data from OpenConcrete.

The mixes were calculated to have a GWP100 of 236-437 kg $CO_2e \cdot m^3$ with a 28-day compressive strength between 5100-9860 psi (while the verification requirements were all <5400 psi). In general, the compressive strength of the concrete was positively correlated with the total amount of cementitious materials, including portland cement, slag, fly ash, and silica fume (Spearman rho value of 0.51 with a p-value of 0.003; Figure 1). At the same time, GWP100 of the concrete was strongly connected to the amount of cement in the mix (Spearman rho value of 0.81 with a p-value of $9\times10^{-9}$). These results were expected as emissions from the cement accounted for 69-96% of the total GWP100 (columns in Figure 2). For mixes with the lowest GWP100, either a significant amount of SCM (slag, fly ash, or silica fume) was used to replace cement, or a blended cement with much lower environmental impacts (e.g., PLC, IS) was used. We also tried to compare the results herein with published EPDs from the concrete supplier for mixes with similar design strength (diamonds in Figure 2; not all concrete suppliers have publicly available EPDs). However, most of the reported GWP100 values were found to be higher than the calculated GWP100, which was attributed to two main reasons: (i) discrepancies in the mix formula despite similar design strength (mix formula was not included in EPDs), and (ii) EPD used industry average LCI (and thus GWP100) for cement and SCMs, whereas plant-specific data was used herein. Overall, this comparison highlights the importance of establishing a consistent protocol (with transparent data reporting) in determining the carbon footprint of concrete mixes. Nonetheless, as portland cement is the most critical driver of emissions, it is feasible for concrete suppliers to substantially reduce the carbon footprint of the concrete mix by switching to blended cement or using SCMs.

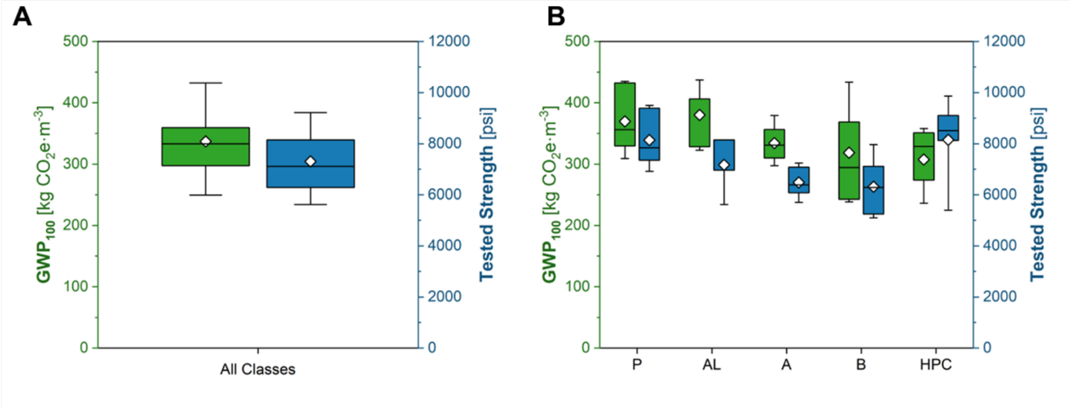

Figure 1. 100-year Global Warming Potential (GWP100) and tested strength at 28 days of all New Jersey Department of Transportation concrete mixes (A) and across the concrete classes (B). Whiskers, box edges, middle lines, and diamonds indicate 10/90%, 25/75%, median, and average data.

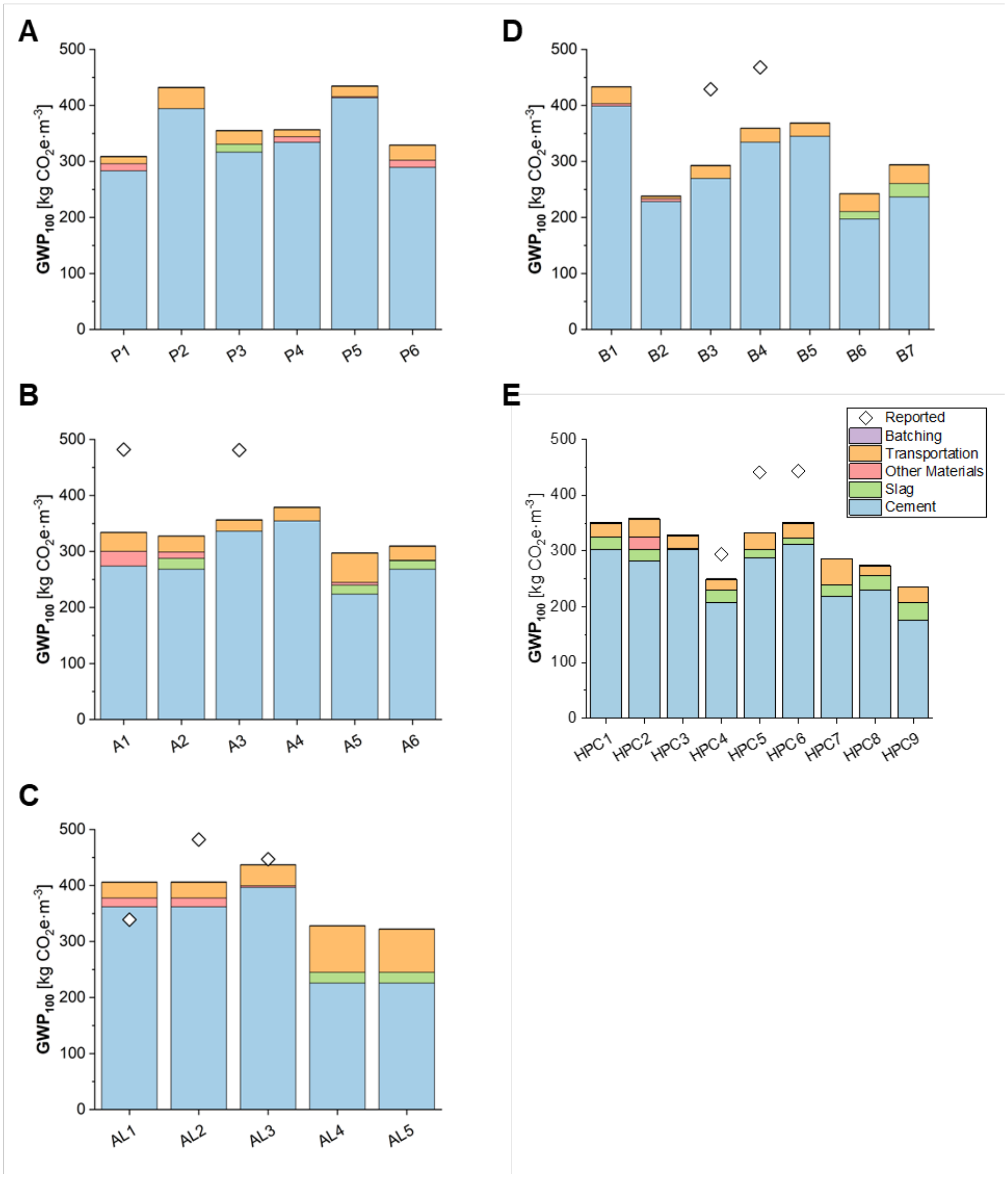

Figure 2. 100-year Global Warming Potential (GWP100) breakdown of all New Jersey Department of Transportation mixes across the classes (columns) with supplier Environmental Product Declaration (EPD) data (diamonds).

These benchmarks provide some preliminary information for benchmarking concrete in New Jersey; however, given the limited data set and range of strengths, they are unlikely to be comprehensive enough to be used statewide. Additionally, they are based on classes of concrete used by the NJDOT, which may not be relevant to use across state agencies. Therefore, a more realistic benchmark from within New Jersey must be determined using a more robust dataset. This process will then need to be updated regularly to ensure that the state continues to reduce the embodied carbon of concrete – as the current benchmark will not remain static as novel materials and design techniques become more standardized.

## 4.5 Thresholds for defining low carbon concrete

Currently, there is no wide range of thresholds for determining whether a concrete mixture should be considered “low-carbon concrete.” Here, we will discuss three implemented or proposed systems: the EPA’s Interim Determination on Low Carbon Construction Materials, New York State’s Buy Clean Program, and ACI Code 323 — Low-Carbon Concrete.

The US EPA has been focusing on supporting low-carbon construction in recent years and has invested significant funding in supporting the development of EPDs and other criteria to determine whether something can be considered low-carbon. In 2022, the EPA released its Interim Determinations for Low Carbon Materials. These values were developed so government agencies could implement the Inflation Reduction Act criteria, which requires “substantially lower carbon building materials.” The EPA considered something “substantially lower carbon” if it was in the top 20 percent regarding the lowest embodied carbon within a particular material class. They then suggest that the 20th percentile should be determined using locally available EPDs or third-party verified LCAs. The EPA’s interim determination does not set a definitive limit for what constitutes a low-carbon material (US Environmental Protection Agency 2022). It should be noted that progress on this set of rules has been ended with the changing priorities of the new federal administration that took office in 2025.

As described above, New York State’s Buy Clean Program sets definitive thresholds for what can be considered “low-carbon” materials. For this program, the local benchmarks determined by the NRMCA/Athena Institute report are used to determine the average performance of concrete in New York. The State has then set a threshold for low-carbon concrete as any concrete mixture with a GWP of 150% or less than the NRMCA/Athena Institute benchmarks (NYS Department of Environmental Conservation 2024).

The American Concrete Institute’s (ACI) Code 323 – Low-Carbon Concrete was finalized in November 2024.In this code, ACI recommends that GWP limits be required on projects of sufficient size (i.e., 50,000 $ft^2$ gross floor area for a building). Smaller projects need to report data but do not need to meet a specific limit. The Code also recommends that jurisdictions utilize local data to develop concrete GWP benchmarks that are accurate for the adopting jurisdiction; a reduction value should then be set based on the local availability of materials. In the absence of or inability to develop those benchmarks, the Code recommends using the NRMCA/Athena Institute regional benchmarks for the adopting jurisdiction’s region. If these benchmarks are used, the Code then recommends that concrete mixtures have a reduction value of 15% over the benchmark – meaning that concrete should have 85% of the benchmark’s GWP. The Code also uses a weighted average of GWP across an entire project. The total project’s average benchmark is calculated by multiplying each concrete class’s benchmark GWP by the concrete volume used in that concrete class and then averaging over the total volume of concrete. A similar calculation is then done to determine the project's actual GWP. This allows the project engineers to use systems with higher than average GWP in some locations that may be needed and offset that with concrete mixtures in other project areas (ACI Committee 323 2024). The code also allows exceptions for pre-cast concrete, concrete with strengths outside of the 2500–8000 psi range, shotcrete, and auger-cast concrete due to a lack of available information on the GWP of these types of systems.

## 4.6 Methods for documenting and certifying concrete as low embodied carbon concrete

Determining or validating the global warming potential of a particular concrete mixture is an integral part of setting low-carbon concrete thresholds. It is vital to use reliable and comparable data to ensure that the reported GWP for a concrete material is accurate. The most common tool to confirm the GWP for a concrete mixture is an environmental product declaration (EPD), a Type III, third-party verified declaration defined by ISO LCA standards (ISO 14044 2006). EPD requirements are set by product category rules (PCR), which define the scope of the LCA needed to create an EPD for a material within a particular category (NSF 1112-19 2024). Currently, there is a PCR for bare ready-mixed concrete, but no PCR exists for pre-cast concrete or other types of systems that may use non-standard mixtures (such as shotcrete).

The EPD is an easy-to-use tool that provides a nutrition label-style set of information regarding the environmental performance of a particular concrete mixture. This is, generally, the preferred tool for confirming the GWP of a concrete mixture. Despite significant increases in the number of available EPDs and a substantial amount of funding dedicated to creating EPDs, EPDs are still rare in parts of the US. Therefore, several groups, including ACI 323, have suggested temporarily allowing the use of a third-party verified LCA for reporting the GWP of concrete. The main drawback is that the data does not necessarily conform to the appropriate PCR, so it may be examined in a different scope than what is in an EPD.

Some groups, such as Marin County and the Port Authority of New York and New Jersey, also provide a prescriptive approach to verifying the GWP of concrete. For Marin County, the current system allows the engineer to provide concrete with a limited amount of portland cement per cubic yard as the mixture design – which is a surrogate for actual GWP, as limiting the portland cement is currently the best tool for reducing concrete GWP (Cardno 2020). The Port Authority of New York and New Jersey provides a prescriptive GWP for each component of a concrete mixture. It allows the submitter to calculate the GWP for their mixtures using the values provided by the Port Authority. These values are industry averages and do not consider the transportation of the materials from the manufacturing facility to the concrete ready-mix facility, so there is a limitation to using them. However, it provides a standardized calculation that the Port Authority can use while EPDs are still rare (The Port Authority of NY and NJ 2021; NJ Business Magazine 2021).

## 4.7 Potential for carbon emissions reductions from low-carbon concrete in New Jersey (2025–2050)

In New Jersey, where infrastructure investment is projected to remain strong through mid-century, transitioning to low-carbon concrete (LCC) presents a significant opportunity to reduce the state's carbon footprint. This section estimates the carbon emissions that could be avoided if New Jersey adopts LCC technologies across its infrastructure projects from 2025 through 2050.

To estimate the potential emissions reduction, we begin by projecting infrastructure spending in New Jersey over the 25-year period from 2025 to 2050. According to the New Jersey Alliance for Action, the state is expected to invest approximately $57.6 billion over two years in infrastructure, or about $28.8 billion annually (New Jersey Alliance for Action 2024). Over 25 years, this equates to a cumulative investment of $720 billion.

Assuming conservatively that 5% of the total $720 billion will be allocated to concrete-related materials and construction, this would amount to $36 billion. The 5% estimate aligns with industry norms for high-level planning when detailed bill-of-materials data is unavailable and provides a conservative baseline that avoids overestimating emissions reductions. This assumption can also be adjusted in future analyses using more granular data from NJDOT or project-specific environmental product declarations (EPDs). Using an average installed cost of $150 per cubic meter of concrete (ShunTool 2025), the assumed budget for concrete translates to an estimated 240 million cubic meters of concrete used over the 25-year period.

Traditional concrete has an average carbon intensity of approximately 350 kilograms of $CO_2$ equivalent (kg $CO_2e$) per cubic meter (Barbhuiya et al. 2025). In contrast, low-carbon concrete—achieved through the use of supplementary cementitious materials (SCMs), blended cements, and optimized mix designs—can reduce this intensity to around 175 kg $CO_2e$ per cubic meter (Arthur et al. 2025). The net reduction in emissions per cubic meter is therefore estimated at 175 kg $CO_2e$.

Multiplying the estimated volume of concrete (240 million $m^3$) by the emissions reduction per unit (175 kg $CO_2e/m^3$) yields a total potential emissions savings of 42 billion kilograms of $CO_2$ equivalent, or 42 million metric tons. This amount represents the cumulative emissions that could be avoided if all concrete used in New Jersey's infrastructure projects between 2025 and 2050 were produced using low-carbon methods.

To contextualize this reduction, it is equivalent to removing approximately 9 million passenger vehicles from the road for one year or powering about 8 million homes with clean energy for the same duration (EPA 2024). These comparisons underscore the significant climate impact that can be achieved through material substitution and design optimization in the construction sector.

The transition to low-carbon concrete in New Jersey's infrastructure projects offers a substantial opportunity to reduce greenhouse gas emissions over the next 25 years. With an estimated 42 million metric tons of $CO_2e$ potentially avoided, this shift would represent a meaningful contribution to the state's climate goals. Achieving this reduction will require coordinated efforts across policy, procurement, and industry practices. As New Jersey continues to invest in its infrastructure, embedding sustainability into material choices will be critical to building a resilient and climate-aligned future.

## 4.8 Recommendations for thresholds and certification methods

The science of reducing carbon emissions associated with the design and implementation of concrete mixtures has significantly advanced in recent years. Despite this, there are still significant challenges in codifying and standardizing methods for reducing emissions, calculating emissions thresholds, and setting reduction targets. In particular, a lack of available data on current emissions within localized regions makes setting GWP targets challenging and uncertain. However, using regional emissions benchmarks and a recently developed model building code from the American Concrete Institute, preliminary guidance for determining what qualifies as "low-carbon concrete" in the state of New Jersey can be developed. Therefore, it is recommended that:

- NJDEP adopt *ACI Code 323-24 – Low-Carbon Concrete* for determining which materials, specifically, are covered under the low-carbon concrete policy. In the preamble the code specifies cast-in-place concrete with specified compressive strength greater than 2,500 psi and less than or equal to 8,000 psi.
- NJDEP adopt *ACI Code 323-24 – Low-Carbon Concrete* as the methodology that should be used to calculate the effective GWP of concrete materials used in a particular project. To determine the GWP for cradle-to-gate, an EPD or LCA as described in ISO 21930 can be used. For an entire project, in section 4.4, the ACI code provides an equation for determining the GWP weighted average for the project and the GWP weighted average benchmark. These two values can then be compared to calculate the reduction in GWP from low carbon efforts.

$$GWP_{project\ avg} = \frac{\sum_{i=1}^{n} GWP_{project\ I} \times Vol_i}{\sum_{i=1}^{n} Vol_i}$$

$$GWP_{benchmark} = \frac{\sum_{i=1}^{n} GWP_{benchmark\ I} \times Vol_i}{\sum_{i=1}^{n} Vol_i}$$

- NJDEP adopt *ACI Code 323-24 – Low-Carbon Concrete* as the methodology that should be used to determine if concrete from a specific project qualifies as low-carbon concrete, using a 15% reduction from the benchmark. The code specifies that the $GWP_{project\ avg} \leq GWP_{benchmark\ avg}$ for higher volume projects related to buildings, pavement and hardscape, bridges, and other structures, however the New Jersey Legislation specifies a reduction of 15% in GWP for new concrete projects in the state.

- NJDEP set preliminary GWP benchmarks based on the Northeast Regional benchmarks defined by the National Ready Mixed Concrete Association in *A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members - Version 3.2*. This document provides environmental impacts for 72 ready mixed concrete (RMC) products/mix designs, estimating the GWP in kg $CO_2e$. The GWP for each product mix design is summarized in Tables 6a through 14b.

- NJDEP develop a process for collection and analysis of local concrete mixture design data such that more accurate and localized GWP benchmarks can be set, and regularly updated, within the state of NJ.

## 4.9 Summary

This report has provided background on the relationship between climate change, greenhouse gases, cement manufacturing, and concrete production. Various solutions to attenuate and even eliminate the emission of greenhouse gases have been described. Many of the solutions require specialty materials that may never have the capability to sustain a supply chain that can thrive within NJ on a long-term basis, either because the materials are not locally available or the manufacturing process is not available on the scale and distribution required for cement manufacturing.

Additionally, a survey of existing policies requiring low-carbon concrete is provided. A preliminary carbon emission benchmark for ready-mixed concrete in the Northeast and New Jersey is provided. Recommendations on the system used for determining low-carbon concrete are discussed and further required action is recommended.

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