GUIDE FOR

Reducing the Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete

IOWA STATE UNIVERSITY
Institute for Transportation

National Concrete Pavement Technology Center
CP Tech Center

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16. Abstract

As part of their sustainability efforts, transportation agencies across the nation are striving to quantify and reduce the cradle-to-gate embodied carbon emissions of their pavement materials—the embodied carbon emissions incurred during the production of paving concrete before it leaves the concrete plant.

This guide offers several practical and implementation-ready strategies for material selection and proportioning that transportation agencies, contractors, and concrete suppliers can use to reduce the cradle-to-gate embodied carbon emissions of paving concrete in readily quantifiable ways. The strategies encompass all aspects of concrete production, including the specification of the materials, processing of aggregates, selection of cementitious materials, proportioning of concrete mixtures, transportation of materials to the concrete plant, and concrete production.

By focusing on reducing the cradle-to-gate embodied carbon emissions of paving concrete, the strategies presented in this guide can both lead to an immediate reduction in embodied carbon emissions and draw attention to the opportunity for broader reductions in other areas of the concrete pavement life cycle. Implementation of these strategies is within the scope of material suppliers and contractors as well as designers, material specifiers, and construction staff, and the resulting reductions in embodied carbon emissions can be quantified through the use of environmental product declarations. Each strategy is described in the guide and further detailed in an Implementation Table to highlight key information and resources available for additional consideration.

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PART 1: GENERAL

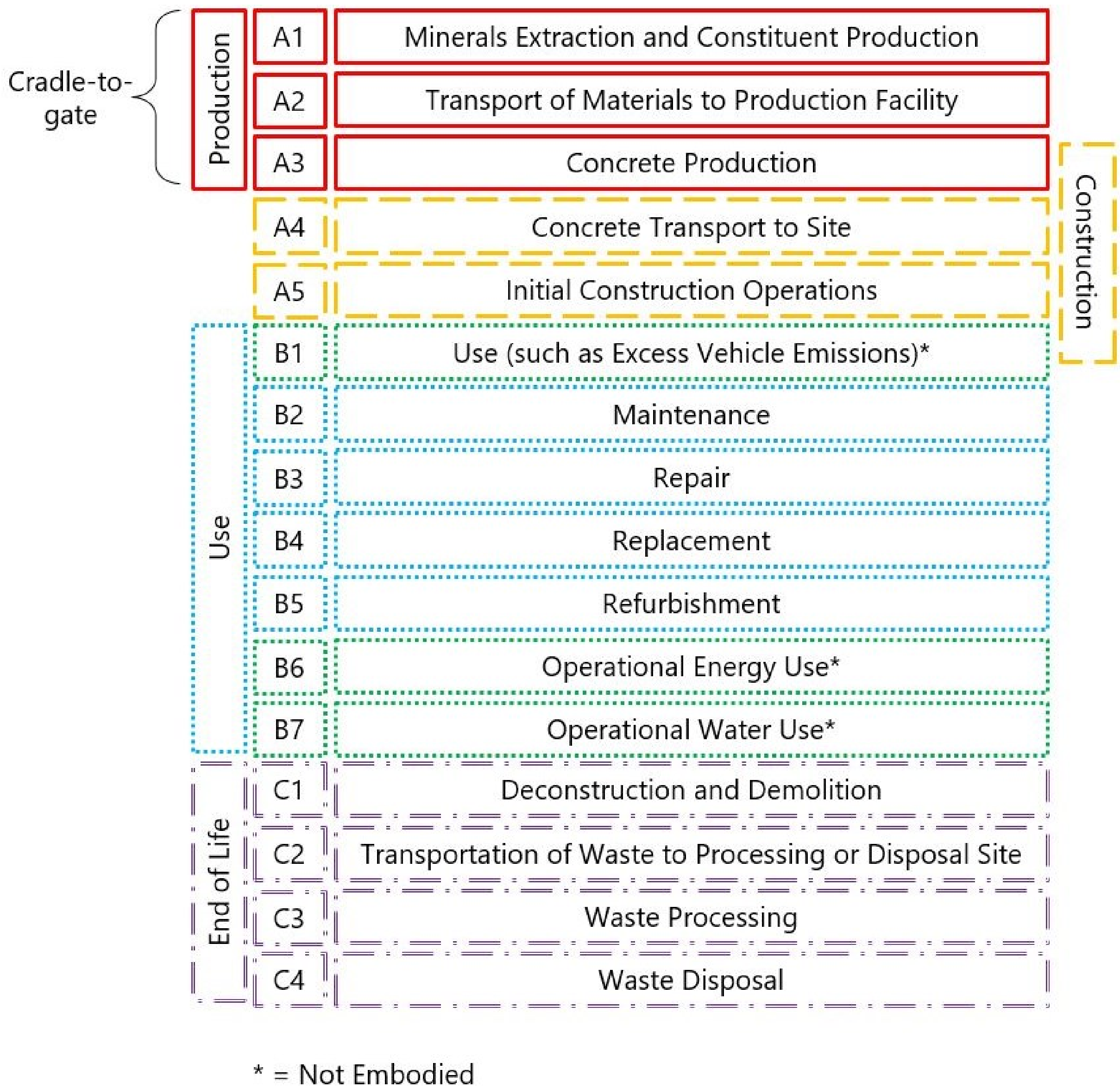
Introduction and Scope

The principles of sustainability are increasingly being applied to the design, construction, and maintenance of pavement and roadway infrastructure. A commonly accepted definition of sustainability is articulated in a 1987 report by the Brundtland Commission, which states, "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). The report further describes sustainability as encompassing three aspects collectively referred to as the "triple bottom line" of sustainable development: environmental, social, and economic impacts. Sustainable solutions are those that recognize and attempt to balance all three aspects in the context of the goals, demands, characteristics, and constraints of a given project. The Federal Highway Administration's (FHWA's) *Towards Sustainable Pavement Systems: A Reference Document* (Van Dam et al. 2015) identifies the features of a sustainable pavement as "system characteristics that encompass a pavement's ability to

1. achieve the engineering goals for which it was constructed,
2. preserve and (ideally) restore surrounding ecosystems,
3. use financial, human, and environmental resources economically, and
4. meet basic human needs such as health, safety, equity, employment, comfort, and happiness."

To partially address the second goal, a growing number of transportation agencies across the nation are striving to quantify the embodied environmental impacts and emissions of their pavement materials. Reducing the embodied greenhouse gas (GHG) emissions (referred to as embodied carbon emissions [ECEs] in this guide) of transportation materials is one way that transportation agencies can reduce the environmental impacts of the transportation systems they construct, own, operate, and maintain. To do this successfully, agencies are in need of clear guidance on strategies to reduce the cradle-to-gate embodied carbon emissions of their transportation construction materials.

This guide offers several strategies for material selection and proportioning that transportation agencies and contractors can use to reduce the cradle-to-gate embodied carbon emissions of paving concrete. In the product life cycle defined by the International Organization for Standardization (ISO), illustrated in Figure 1, the cradle-to-gate production of a material corresponds to the Production stage and includes Modules A1 through A3 (hereafter referred to as A1–A3). While the Construction stage (Modules A4 through A5), Use stage (Modules B1 through B5), and End of Life stage (Modules C1 through C4) also present significant opportunities to reduce the embodied carbon emissions of a transportation system, these stages are not included in the scope of this guide. Despite not being included, these stages of a pavement life cycle also present significant opportunities to reduce the life-cycle GHG emissions of concrete pavement. As life-cycle assessment (LCA) use-phase modeling becomes more robust, these factors are likely to be included to provide a more complete assessment of the carbon emissions associated with a given concrete pavement.



FHWA, adapted from ISO 21930

Figure 1. Life-cycle stages

By focusing on reducing the cradle-to-gate embodied carbon emissions of paving concrete during the Production stage, the strategies presented in this guide can serve as an important early step in bringing attention to the need for broader carbon reduction while implementing quantifiable change. The ability to reduce the embodied carbon of concrete in a given location certainly depends a great deal on existing practice and the availability of concrete-making materials; a dramatic change in the types of cementitious materials used may be needed in some locations, while simple changes in mixture proportioning may be needed in others. In all cases, however, the strategies described in this guide are within the scope of material suppliers and contractors as well as designers, material specifiers, and construction staff representing the interests of public/private agencies and owners of the assets. Most of the strategies presented can be implemented immediately to produce positive short-term improvements while broader, longer term actions are planned. Early successes achieved during the Production stage can be built upon to further reduce embodied carbon emissions in later stages of the concrete life cycle.

Strategies are presented for reducing the cradle-to-gate embodied carbon emissions of concrete throughout all aspects of the Production stage, including raw material acquisition and processing (A1), transportation of materials to the concrete plant (A2), and in-plant concrete production (A3). Strategies to reduce the impacts of aggregates, whether mined or recycled, are discussed, while strategies to be utilized by cement producers (e.g., alternative fuels, renewable energy for cement plant operations, carbon capture) and supplementary cementitious materials (SCMs) suppliers (e.g., waste recovery, processing options, CO_2 mineralization) are not discussed in detail because these processes are not under the direct control of concrete suppliers or agency representatives. However, reductions in embodied carbon emissions will be evident in each concrete mixture's environmental product declaration (EPD), which incorporates the EPDs provided to the concrete supplier for the individual concrete constituents. The impacts of transporting constituent materials to the concrete plant (A2) are also accounted for in the EPD provided by the concrete supplier for each concrete mixture.

In describing the strategies for reducing the embodied carbon emissions of concrete, the guide emphasizes that concrete mixture proportioning should consider the economic and workability aspects of the mixture while ensuring that all performance requirements are met, including all engineering (e.g., strength, durability) and environmental requirements. This requires diligence in selecting desirable materials, the use of an appropriate approach to determine concrete mixture proportions, and adherence to best practices during concrete manufacture to ensure that the concrete is uniformly produced to facilitate proper placement, finishing, and curing.

Partnership Approach

Lowering the embodied carbon emissions of concrete requires a partnership effort, and for this effort to be successful it is important to engage relevant stakeholders early in the process. Among many criteria, public agencies desire innovations that are scalable, practical, and safe (Jamshidi 2024). Since concrete paving mixtures are specified by owners and consulting engineers, provided by concrete producers, and placed by concrete paving contractors, providing this diverse stakeholder group sufficient opportunity to discuss, understand, and contribute to these goals is important, even before construction begins.

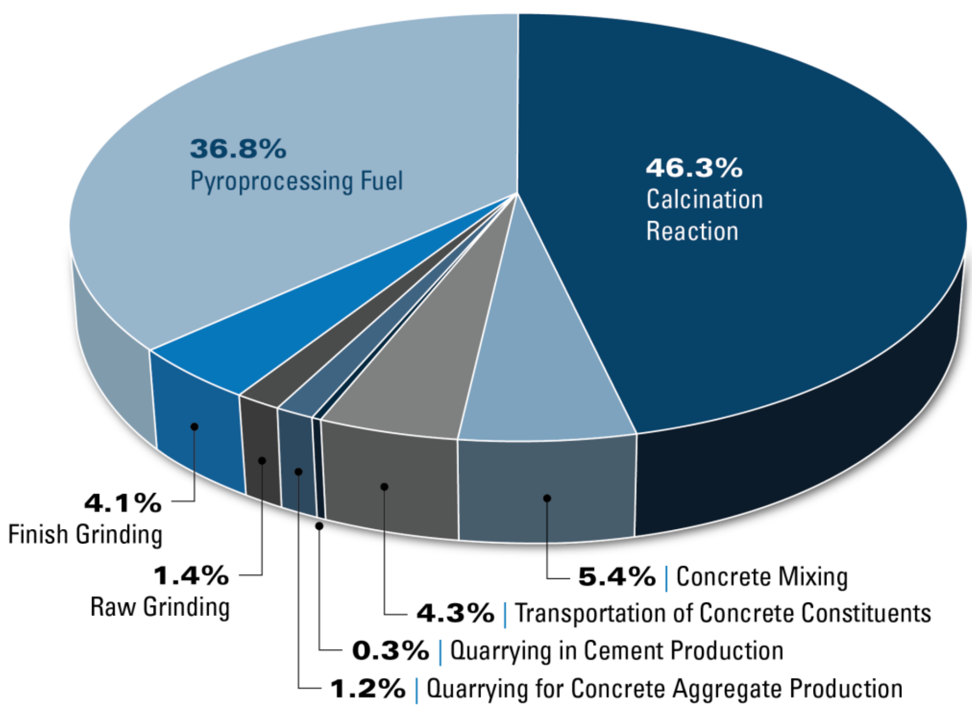
A successful partnership involves early engagement of the affected parties in a planning or partnering meeting where the goals for reducing embodied carbon emissions are communicated and discussed. Concrete producers and other materials suppliers awareness of these goals can bring value, because they can often have access to expertise and resources that owners and contractors sometimes do not, have significant expertise with locally available materials, and can play a key role in reducing embodied carbon emissions. Engaging concrete producers in the conversation allows them to contribute to the broader project goals by potentially selecting constituent materials that reduce the embodied carbon emissions of the concrete. Concrete producers' expertise with locally available materials also gives them in-depth understanding of how these materials can be combined and how interactions and compatibility can impact performance. Engaging this expertise facilitates compliance with the overarching goal to optimize concrete mixtures while achieving engineering goals and quantifiable carbon emission reduction. At the same time, owners/agencies and their representatives must recognize that current specifications may limit certain opportunities for reducing embodied carbon emissions in concrete mixtures. Examples of such barriers are discussed in subsequent sections of this guide. Owners should also be mindful of an increased need for quality control/quality assurance (QC/QA) when using novel materials or new and innovative mixtures.

Given this reality, taking specific actions early in the process to make all parties aware of the project's goals for reducing embodied carbon emissions makes it much more likely that these goals will be achieved. Communicating with partners early and often during project planning may avoid the need for changes and adjustments after the project is well underway, when it would be much more difficult to modify an accepted mixture, change sources, adjust specifications, and so on.

Portland Cement and Embodied Carbon Emissions of Concrete

Concrete is humankind's most widely used construction material. Based on unit of mass, concrete has one of the lowest amounts of embodied carbon emissions of all construction materials (Barcelo et al. 2014), yet the widespread use of concrete causes it to be one of the largest single sources of embodied carbon emissions. According to the United States Environmental Protection Agency (EPA), the production of portland cement was linked to approximately 1.08% of the total US embodied carbon emissions in 2022 (EPA 2023a, 2023b).

Today's concrete technology is largely dependent upon portland cement clinker as the main binding material. For typical concrete mixtures, it is estimated that almost 90% of the embodied carbon emissions in a concrete mixture at the gate of the concrete plant is from the production of portland cement. Production of portland cement is both energy and carbon intensive due to the mining, crushing, and grinding of raw materials; fuel combustion in the kiln; calcination of limestone; and finish milling (Choate 2003). The remaining 10% of embodied carbon emissions is due to the mining, transporting, blending, and mixing of materials at the concrete plant. A breakdown of these percentages is illustrated in Figure 2. The impacts of these activities can be summarized in terms of global warming potential (GWP), which equates the effects of various GHGs to the equivalent effect of CO_2 and is expressed in terms of embodied CO_2 equivalent (CO_2-eq). Overall, the GWP of portland cement produced in the United States and Canada is approximately 0.9 kg CO_2-eq per kg of portland cement.



Adapted from Choate 2003

Figure 2. CO_2 emissions for quarrying, cement manufacturing, and concrete production

Implementation Considerations

Over the short term, reducing the embodied carbon emissions in the production of paving concrete will require optimizing the amount of portland or blended cement in the concrete to reduce the amount of portland cement clinker used. This introduces several implementation considerations:

- Portland cement reacts with water and generates heat. This heat is needed to sustain and accelerate the hydration reactions that support strength gain. Reducing the amount of portland cement in the concrete often reduces the heat of hydration and alters the early-age strength gain, particularly under low ambient temperature conditions.
- Concrete with reduced cradle-to-gate embodied carbon emissions can have a lower total cementitious content than traditional mixtures. This reduction in cementitious content makes moisture control at the plant important because small variations in water content will have a more profound effect on the water-to-cementitious materials (w/cm) ratio, which affects strength and durability.
- Some cementitious materials used as a replacement for clinker are more finely ground than portland cement. Using finer materials impacts the water demand and the rate of bleeding of fresh concrete. Contractors may need to modify their finishing operations to adjust for these changes.
- Overall, changes to concrete that reduce embodied carbon emissions can alter the long-term hardened properties of the concrete. In many cases, these changes are small and have little impact on future life-cycle stages. In other cases, the changes may improve the long-term hardened properties in terms of improved strength, lower permeability, reduced shrinkage, and greater durability. It is also possible, however, that the changes could result in poorer long-term performance. It is therefore necessary that diligence be exercised to ensure that the concrete meets the required long-term engineering properties. This may require additional testing beyond what is typically required to reduce the risk of poor future performance.

Inadvertent Barriers Within Agency Specifications

As illustrated in Figure 2, the manufacturing of portland cement is overwhelmingly responsible for the cradle-to-gate embodied carbon emissions of concrete. The strategies for reducing embodied carbon emissions described in this guide are therefore largely focused on reducing the amount of portland cement used in concrete. While reducing portland cement content can pose technical challenges, a significant barrier to immediate reduction often lies within current agency specifications. Agencies should consider the following:

- Agencies should not limit the type of cement that can be used. In addition to AASHTO M 85/ASTM C150 portland cement, AASHTO M 240/ASTM C595 blended cement should be allowed. Consider permitting the use of ASTM C1157 performance hydraulic cement if not currently accepted. Agencies should permit a wide range of SCMs with high replacements rates beyond those traditionally used.
- Some agencies have eliminated minimum cementitious materials content requirements for paving concrete, while many agencies require relatively low minimums of around 500 lb/yd^3 or lower. Requiring a minimum cementitious materials content above 500 lb/yd^3 may create an unneeded barrier to reducing the embodied carbon emissions of the mixture.
- There are times when early strength is needed, such as when a pavement needs to be rapidly opened to traffic. However, specifications often require pavements to achieve design strength within the first 7 to 10 days even when high early-age strength is not needed. Over-specifying design strength or requiring that design strength be achieved at early ages can lead practitioners to over-cement the concrete mixture to achieve early strength gain, which increases the embodied carbon emissions of the concrete. Shifting the age of acceptance testing from 28 days to 42 days or 56 days provides additional time for pozzolans

to react and reflects the long-term strength of concrete made with a high amount of portland cement replacement.

Achieving Engineering Goals

The first goal of a sustainable pavement system, as discussed in *Towards Sustainable Pavement Systems: A Reference Document* (Van Dam et al. 2015), is to achieve the engineering goals for which it was constructed. When constructing a pavement system containing concrete with reduced embodied carbon emissions, care should be taken to define engineering goals that will help reduce maintenance, decrease roughness, and achieve the desired degree of safety and service life. Sacrificing these engineering goals can lead to an increase in the life-cycle embodied carbon emissions and adversely impact the total life-cycle emissions, even if these do not show up in a material EPD that only considers A1–A3. The use of paving concrete with reduced embodied carbon emissions must not compromise service life and ideally would increase the lifetime of the pavement for additional reductions in life-cycle embodied carbon emissions.

Additionally, the quality of materials and workmanship has a direct impact on pavement longevity and condition and is therefore an important consideration with respect to life-cycle embodied carbon emissions and the emissions associated with infrastructure users.

Use of This Guide

The target audiences for this guide include agency personnel involved in specifying concrete paving mixtures, their consultants, and contractors and concrete mixture designers. The guide focuses on several strategies that are highlighted for implementation by specifiers and mixture designers of paving concrete. While the strategies to reduce the cradle-to-gate embodied carbon emissions of paving concrete are listed separately, they must be considered holistically since the effects of some may offset the effects of others. For example, a high SCM substitution rate may not be possible if a switch is made from an AASHTO M 85/ASTM C150 portland cement to an AASHTO M 240/ASTM C595 blended cement. In this case, it is important that the overall embodied carbon emissions of the paving concrete be reduced regardless of whether the embodied carbon emissions of the cementitious binder are reduced.

The following five strategies, used separately or in combination, can result in measurable reductions in the cradle-to-gate embodied carbon emissions of paving concrete:

- **Strategy 1. Target the cementitious binder**. Select a cement with reduced embodied carbon emissions. For example, replace an AASHTO M 85/ASTM C150 cement combined with 15% AASHTO M 295/ASTM C618 coal ash with an AASHTO M 240/ASTM C595 Type IT cement that has a total base portland cement content of 50%.
- **Strategy 2. Target the concrete mixture to optimize binder content**. For a given binder, reduce the total cementitious content (e.g., from 564 to 500 lb/yd^3) through optimized aggregate grading.
- **Strategy 3. Reduce the cradle-to-gate embodied carbon emissions of aggregates**. Use aggregate with reduced embodied carbon emissions. For example, use locally available aggregate where possible or use recycled coarse aggregate produced during an earlier stage of the project if the aggregate's EPD indicates lower associated embodied carbon emissions than available virgin aggregate sources. In the latter case, ensure that the recycled aggregate meets all engineering and durability requirements (e.g., that the aggregate is not susceptible to alkali-silica reactivity [ASR]).

- **Strategy 4. Target mixture performance requirements**. Use performance specifications for mixture proportioning and acceptance to spur development of innovative mixtures. For example, use AASHTO R 101 and implement performance requirements for paving concrete to ensure long-term durability.
- **Strategy 5. Consider other factors**. Identify other strategies to reduce the embodied carbon emissions of the concrete. These may include locating the concrete production plant closer to the project site to reduce transportation distances or utilizing CO_2 mineralization into calcium carbonate to sequester CO_2.

Users of this guide should approach each strategy independently but ultimately consider them together when specifying and proportioning a mixture. Each strategy is accompanied by an Implementation Table in Appendix A that provides background information about the strategy, a high-level overview of how the strategy can result in lower embodied carbon emissions, and actions and steps that can be taken to implement the strategy. This information is presented to help practitioners accelerate and facilitate implementation of these strategies based on past successes.

A crucial final step that is essential to reduce the cradle-to-gate embodied carbon emissions of paving concrete is rigorous verification of the reduction in embodied carbon emissions. Verification is addressed in this guide under its own heading: Quantifying. The Quantifying chapter highlights the best way to assess the cradle-to-gate embodied carbon emissions of paving concrete, namely, through the use of an EPD. In cases where an indication of the embodied carbon emissions is needed before an EPD can be generated, the Quantifying chapter also discusses existing tools that can be used to develop a preliminary estimate, while Appendix B presents a more detailed example method to estimate the embodied carbon emissions of paving concrete. These approaches are not to be used in place of an EPD but can serve as a first-order approximation to assess the impacts of the employed strategies until an EPD can be produced. Specifiers should not use these estimation tools for the purposes of accepting a material or making informed decisions as part of the materials testing and evaluation process.

PART 2: STRATEGIES

The strategies presented in this guide are supplemental to the proportioning methods and tools in use by concrete mixture designers. The strategies are therefore intended not to replace existing proportioning methods but to provide approaches that can reduce the embodied carbon emissions of paving concrete relative to current practice. The strategies are presented in order of their effectiveness for reducing the cradle-to-gate embodied carbon emissions in typical applications, with Strategy 1 offering the greatest opportunity for improvement.

When proportioning paving concrete, each component of the system presents an opportunity to contribute to the goal of achieving an overall reduction in embodied carbon emissions. These system components include the cementitious binder used (cement and SCMs), the amount of cementitious binder in the concrete (reduced through optimization of aggregate grading), and the other constituents selected, including aggregates and admixtures. The embodied carbon emissions can also be reduced by reducing emissions associated with the transportation of materials from their sources to the concrete plant and improved efficiency during material handling, batching, and mixing at the concrete plant.

Strategy 1: Target the Cementitious Binder

Although efficiencies and optimizations need to be considered throughout the production stage, the key to an immediate and significant reduction in the embodied carbon emissions of paving concrete is clear: reduce the proportion of cementitious binder that is portland cement clinker. Replacing clinker with limestone at the cement plant (i.e., specifying AASHTO M 240/ASTM C595 Type IL portland-limestone cement) and with SCMs reduces the amount of portland cement clinker and therefore reduces embodied carbon emissions.

Concrete suppliers typically have two silos at their concrete plants for cementitious materials: one for cement and the other for an SCM. In the past, the cement silo has almost universally been filled with an AASHTO M 85/ASTM C150 portland cement selected to meet local conditions, including sulfate exposure in local soils (i.e., Type I, Type II, or Type V). However, in some regions the primary cement has recently changed to an AASHTO M 240/ASTM C595 Type IL portland-limestone cement containing up to 15% interground limestone, though 12% is the practical limit at most cement plants. This type of cement can include modifiers to meet the local soil conditions (i.e., in Type IL[MS] cement) and as of 2023 has become the prevalent cement used in the United States (USGS 2023).

Meanwhile, SCM replacement is most often performed at the concrete plant. The SCMs, most commonly coal ash, slag cement, or natural pozzolans, are stored in the second silo and largely reflect local availability and preference.

Increasing SCM use will lower embodied carbon emissions when SCMs are used as a direct replacement for portland cement on a mass basis. Further, SCMs often have a positive effect on the workability, durability, and long-term strength gain of paving concrete (Taylor et al. 2019).

A potential downside of increased SCM use with a corresponding reduction in clinker content is that, in most cases, the hydration reaction slows, resulting in slower setting and a slower rate of strength development. This change from traditional hydration kinetics can impact all phases of construction, especially during cooler weather, as follows:

- A reduced rate of bleeding and a slower set may impact finishing operations and require extra diligence in curing, which must be applied earlier and more thoroughly. The visual cues that finishers typically rely on for determining when to finish the concrete may not appear in the same manner, requiring extra diligence from the finishers.
- It is important to time sawing based on property development and environmental conditions. A slower set may delay the sawing window for jointing and can result in increased risk of cracking.
- Slower strength gain can delay the timing of form removal and the opening of the pavement to both construction and public traffic.
- Slower strength development may mean that the age at which the concrete reaches the desired design strength is delayed, suggesting that the date of acceptance may need to be shifted from 28 days to 42 days or later. This shift can impact the speed of construction and may shorten the construction window during the year in northern climates. It is noted, however, that SCM use almost always results in higher long-term strength and lower permeability, leading to longer service life.

Figure 3 illustrates the effects of various SCMs on hardened concrete properties.

	Fly ash				Natural pozzolans		
	Class F	Class C	Slag cement	Silica fume	Calcined shale	Calcined clay	Metakaolin
Early age strength gain	↓	↔	↕	↑	↓	↓	↑
Long term strength gain	↑	↑	↑	↑	↑	↑	↑
Abrasion resistance	↔	↔	↔	↔	↔	↔	↔
Drying shrinkage and creep	↔	↔	↔	↔	↔	↔	↔
Permeability and absorption	↓	↓	↓	↓	↓	↓	↓
Corrosion resistance	↑	↑	↑	↑	↑	↑	↑
Alkali-silica reactivity	↓	↓	↓	↓	↓	↓	↓
Sulfate resistance	↑	↕	↑	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔	↔
Deicer scaling resistance	↔↓	↔↓	↔↓	↔↓	↔↓	↔↓	↔↓

Effect depends on material composition, dosage, and other mixture parameters; these general trends may not apply to all materials and therefore testing should be performed to verify the impact.

Key:
- ↓ lowers
- ↑ increases
- ↕ may increase or lower
- ↔ no impact
- ↔↓ may lower or have no impact

Kosmatka and Wilson 2016, © 2016 PCA, used with permission

Figure 3. Effects of supplementary cementitious materials on hardened concrete properties

State highway agencies (SHAs) and local agencies should allow and encourage the use of cementitious binders in which the clinker is interground with limestone and that contain SCMs at the highest practical level, being cognizant of the impacts of slower set times and strength development. The ages when the pavement is opened to traffic and when acceptance testing is conducted may need to be shifted to accommodate slower strength gain, particularly for construction done during cooler weather. More information on the use of

SCMs can be found in the second edition of *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (Taylor et al. 2019).

The approach taken in this guide to reduce the embodied carbon emissions of the cementitious binder system is depicted in Figure 4 (Chart 1). The tables cited in this figure are presented in Appendix A. The use of this figure is described in the following sections.

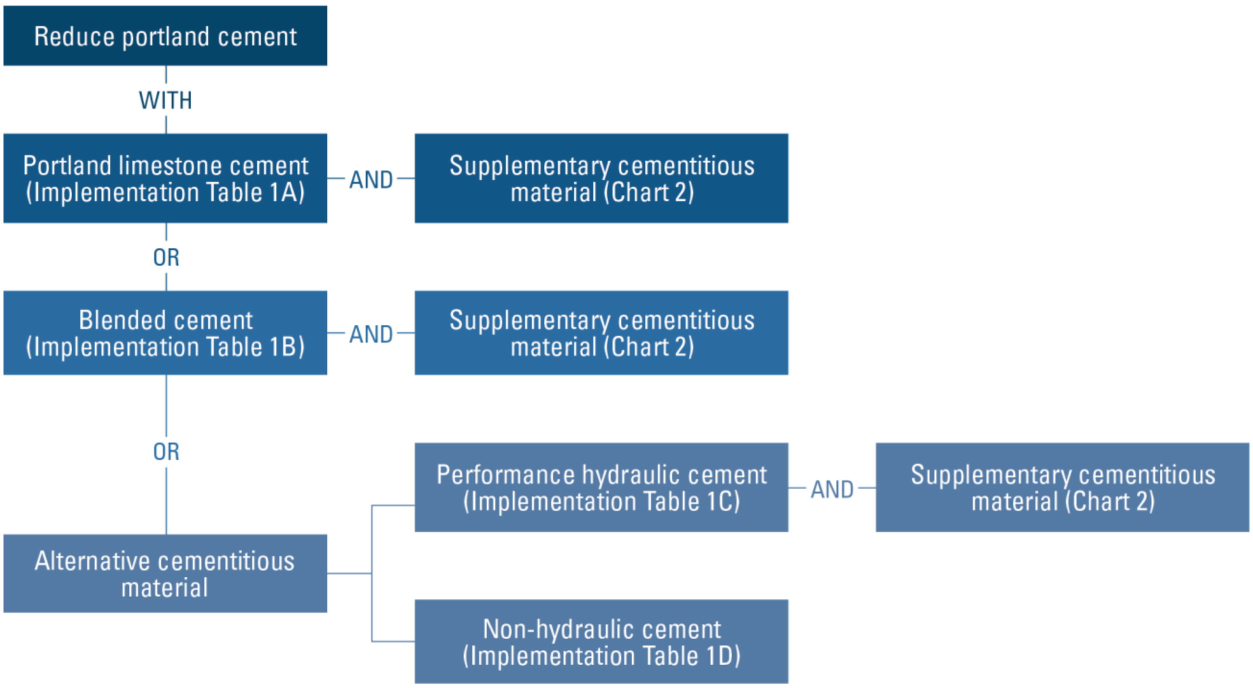


Figure 4. Chart 1: Pathways to reduce cradle-to-gate embodied carbon emissions targeting the cementitious binder system

Reduce Amount of Portland Cement Clinker (AASHTO M 85/ASTM C150)

The most effective strategy to reduce the cradle-to-gate embodied carbon emissions of paving concrete is to reduce the amount of portland cement clinker in the mixture. The first step to accomplish this reduction is to reduce the proportion of portland cement clinker in the cementitious binder by replacing portland cement (AASHTO M 85/ASTM C150) with portland-limestone cement (AASHTO M 240/ASTM C595 Type IL) or a blended cement containing an SCM (AASHTO M 240/ASTM C595 Type IP, IS, or IT). The following types of blended cement are included in the AASHTO M 240/ASTM C595 specification:

- **Type IL Portland-Limestone Cement (AASHTO M 240/ASTM C595 Type IL)**. Type IL blended cement is often formulated in such a way that it can be specified as a nearly direct replacement for portland cement, with AASHTO M 240/ASTM C595 noting that the performance of Type IL cement must be verified through mixture proportioning and testing. By specification, the limestone can constitute up to 15% by mass of the blended cement, although in practice replacement levels of 12% to 13% are common. At this replacement level and without changing the cement content, it is estimated that the use of Type IL cement reduces embodied carbon emissions by up to 8% to 10% compared to conventional portland cement. See Implementation Table 1A for more information.

- **Type IP Portland-Pozzolan Cement (AASHTO M 240/ASTM C595 Type IP)**. Type IP cement is a blend of portland cement and up to 40% pozzolan by mass. The pozzolans used can include coal ash, natural pozzolans, or silica fume. See Implementation Table 1B for more information.
- **Type IS Portland-Slag Cement (AASHTO M 240/ASTM C595 Type IS)**. Type IS cement is a blend of portland cement and up to 95% slag cement by mass. See Implementation Table 1B for more information.
- **Type IT Ternary Blended Cement (AASHTO M 240/ASTM C595 Type IT)**. Type IT cement is a blend of portland cement with two other constituents, either two SCMs or one SCM and ground limestone. The combination of pozzolan, limestone, and slag cement can constitute up to 70% of a Type IT cement, with a pozzolan content of no more than 40% by mass and a limestone content of no more than 15% by mass. See Implementation Table 1B for more information.

Portland cement can also be replaced with other hydraulic cements specified under ASTM C1157, Standard Performance Specification for Hydraulic Cements. The use of ASTM C1157 performance hydraulic cements may reduce the embodied carbon emissions of cementitious binders compared to AASHTO M 85/ASTM C150 portland cement and AASHTO M 240/ASTM C595 blended cement. The specification requirements ensure that cements specified under ASTM C1157 meet certain testing-based performance criteria rather than prescriptive limits. Implementation Table 1C discusses ASTM C1157 performance hydraulic cements.

Alternatively, portland cement can be replaced with non-hydraulic inorganic cements, which set and harden due to alkali activation and chemical reactions that result in non-hydrated alumino-silica reaction products. These materials are at times referred to as geopolymers or inorganic polymer cements and are discussed in Implementation Table 1D.

Increase Use of Supplementary Cementitious Materials

In addition to the options described above for lowering the portland cement clinker content of the cement, SCMs can be added at the concrete plant to further reduce the cradle-to-gate embodied carbon emissions of cementitious binders, as shown in Figure 4 (Chart 1). The use of SCMs as a binder replacement is already common practice in many markets, but coupling increased SCM replacement rates at the plant with the use of cementitious binders designed to reduce embodied carbon emissions raises additional considerations with respect to the early-age behavior of the concrete.

SCMs are materials that, when blended with portland cement, contribute to the properties of the concrete through pozzolanic activity, hydraulic activity, or both. (For detailed information on hydration, see Taylor et al. [2019].) Common SCMs are shown in Figure 5 (Chart 2) and discussed in Implementation Tables 2A through 2D and are specified as follows:

- AASHTO M 295/ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
- AASHTO M 302/ASTM C989, Standard Specification for Slag Cement for Use in Concrete and Mortars
- AASHTO M 307/ASTM C1240, Standard Specification for Silica Fume Used in Cementitious Mixtures
- ASTM C1866, Standard Specification for Ground Glass Pozzolan for use in Concrete

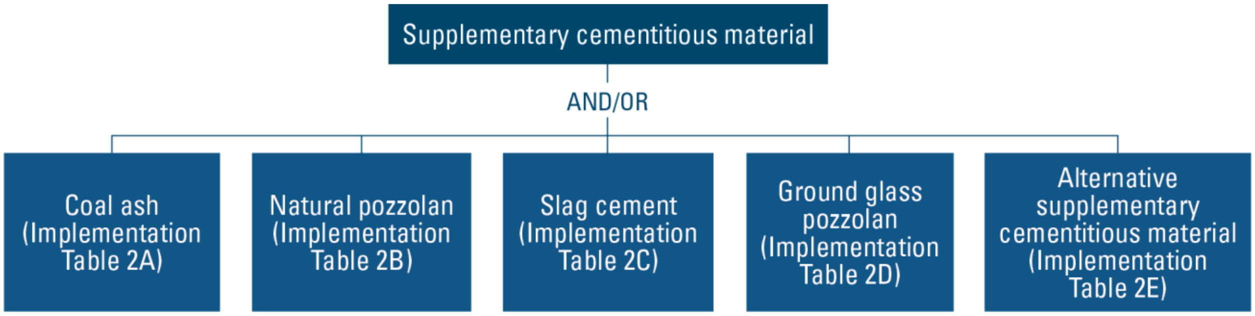


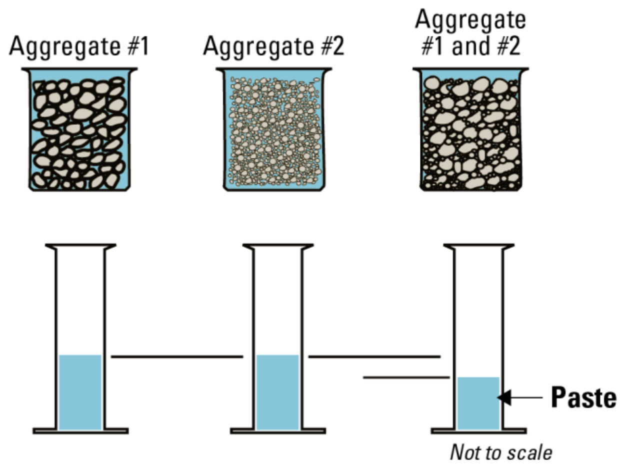
Figure 5. Chart 2: Types of supplementary cementitious materials

In addition to the SCMs noted in the specifications listed above, several alternative SCMs are currently or will soon be on the market that do not fit under current standard specifications but may offer opportunities for reducing embodied carbon emissions. These are discussed in Implementation Table 2E.

Strategy 2: Target the Concrete Mixture to Optimize Binder Content

Once the portland cement clinker content of the cementitious binder is reduced, the next strategy is to potentially reduce the cementitious binder content in the concrete. Reducing the binder content will not only reduce the embodied carbon emissions of the concrete but, assuming that the w/cm ratio remains constant, also reduce shrinkage and improve durability without impacting long-term strength (Obla et al. 2017). If the w/cm ratio remains constant, a reduction in cementitious binder has a corresponding decrease in added water, and both factors together result in a lower cementitious paste volume (i.e., the percent volume of cementitious materials and water in a cubic yard of concrete). AASHTO R 101 recommends a maximum paste volume of 25% for paving mixtures. This limit represents a good target, but regional differences in materials may require the need for a slightly higher paste volume.

Reducing the total cementitious materials content must be accomplished while maintaining the required fresh concrete properties, including workability and air content, as well as the required hardened concrete properties, including strength and durability. The general approach to reducing the binder content is through optimized aggregate grading, in which the aggregate particle size distribution is selected to facilitate aggregate packing without compromising workability, as illustrated in Figure 6. Improving aggregate packing allows aggregate to replace paste without negative impacts. Paving concrete featuring optimized aggregate gradation is more cost-effective than concrete without optimized aggregate grading and often exhibits improved workability and enhanced durability.



PCA, used with permission

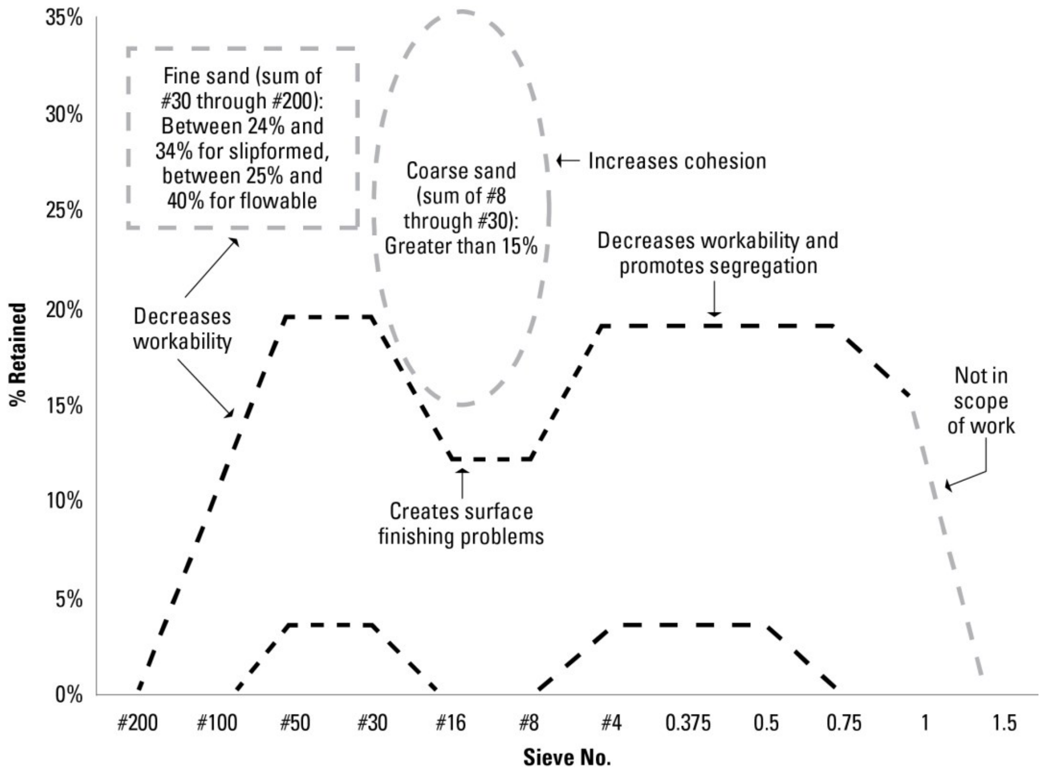
Figure 6. Conceptual illustration of optimized aggregate system

Several excellent resources are available that address optimized aggregate grading:

- *Integrated Materials and Construction Practices for Concrete Pavements: A State-of-the-Practice Manual, 2nd Edition* (Taylor et al. 2019)
- *Blended Aggregates for Concrete Mixture Optimization: Best Practices for Jointed Concrete Pavements* (Taylor and Fick 2015)
- *Improving Concrete through Optimizing Aggregate Gradation: Findings from the FHWA Mobile Concrete Trailer* (FHWA 2017)
- *Tarantula Curve* (Ley 2023)

The underlying philosophy of these resources involves reassessing how the aggregate portion of concrete mixtures is viewed. While traditional approaches to concrete aggregate grading have been concerned with the composition of coarse and fine aggregate, the characteristics of the combined aggregate grading are of greater importance for the mixture and should instead be evaluated. In other words, the focus of aggregate grading should be on ensuring that the combined aggregate meets a given specification rather than on whether the individual aggregate sources meet specific sieve requirements (FHWA 2017). When the aggregate grading is optimized, a minimum amount of paste is needed to fill the void space that exists between the aggregate particles, just enough to separate the particles slightly and act as a lubricant to ensure mixture workability. Additional paste beyond what is needed has little to no benefit and in fact may be detrimental to mixture economy and performance because it can result in increased shrinkage, permeability, and risk of cracking. The excess paste also contributes to increasing the embodied carbon emissions of the mixture.

Although it is possible in some cases to achieve an optimized aggregate grading with the two traditional aggregate sources (i.e., coarse and fine aggregate), most often the use of a third or even a fourth aggregate source is needed to provide the intermediate-sized aggregate required to fill in the gaps between the two. Multiple tools are available to assist the concrete mixture designer in combining multiple aggregate sources to select an optimized aggregate grading. These tools are reviewed in several documents, including Taylor et al. (2019) and Taylor and Fick (2015). The Tarantula Curve, shown in Figure 7, has been found to be a good approach to guiding the development of an optimized aggregate grading for slipform paving, as described in Ley and Cook (2014) and Ley 2023). Implementation Table 3 describes an approach to achieve optimized aggregate grading.



Recreated from M. Tyler Ley, used with permission

Figure 7. Tarantula Curve

Strategy 3: Reduce the Cradle-to-Gate Embodied Carbon Emissions of Aggregates

In addition to the specific aggregate grading used in a mixture, as discussed under Strategy 2, the aggregates themselves also contribute to the embodied carbon emissions of the concrete, though to a lesser degree than the cementitious materials. Although aggregates have relatively low embodied carbon emissions per unit mass compared to other mixture constituents, they make up the largest share of mass in concrete and therefore have an impact on the overall embodied carbon emissions. Aggregates that meet AASHTO M 6 and AASHTO M 80 (ASTM C33) have proven to be satisfactory for use in concrete. Natural aggregates are the most used, with crushed stone being mined (often by blasting) and crushed through hard rock quarrying operations and with sand and gravel being excavated and processed (potentially including some crushing for sizing) from pits, most often from alluvial sources.

The primary considerations in choosing aggregate sources to support a reduction in the cradle-to-gate embodied carbon emissions of concrete are as follows:

- Aggregate shape and texture affect water demand, workability, and finishability. This is especially true for manufactured fine aggregates, the use of which can result in a harsh mixture that is difficult to finish. The conventional approach to address highly angular and/or coarsely textured aggregates is to increase the paste volume (through an increase in both the cementitious materials and water content), which negatively impacts the embodied carbon emissions of the concrete. For example, if the only available local fine aggregate is manufactured, a balance may need to be struck between using this material, with the associated increase in the cementitious materials content needed to provide a workable, long-lasting concrete mixture, and transporting a natural fine aggregate a longer distance to achieve a lower paste volume.

- Aggregates must be durable. The primary durability concern is alkali-aggregate reactivity, which includes ASR and alkali-carbonate reactivity (ACR). AASHTO R 80/ASTM C1778 should be followed to identify potentially deleteriously reactive aggregates and to select appropriate preventive measures to minimize the risk of expansion when such aggregates are used in concrete. Preventive measures for ASR-susceptible aggregates include avoiding the use of the reactive aggregate, limiting the alkali content of the concrete, using blended cement, using SCMs, using lithium nitrate as an admixture, or a combination of these measures. There are no preventive measures for ACR other than avoiding the use of the reactive aggregate.
- Aggregates in some regions are also susceptible to damage when subjected to freezing and thawing when in a high degree of saturation. This damage manifests as concrete pavement deterioration, notably D-cracking. SHAs in regions that experience freezing and thawing cycles have developed mitigation strategies to address aggregate freeze-thaw damage largely based on AASHTO T 161/ASTM C666. (For example, see Chapter 4 in Harrington et al. [2018]). These mitigation strategies should be followed.

Several resources describe aggregates for use in concrete, including Taylor et al. (2019) and Wilson and Tennis (2021). Note that aggregate mining, processing, and transporting operations have environmental and social impacts beyond the embodied carbon emissions of concrete (Van Dam et al. 2015). However, the guidance provided in the present document focuses exclusively on the cradle-to-gate embodied carbon emissions. Figure 8 and Implementation Table 4 show the pathways for reducing the embodied carbon emissions of paving concrete through consideration of the aggregates used in the mixture. These pathways are divided into the following categories:

- Reduce embodied carbon emissions in the production and transportation of aggregates
- Use recycled, waste, and byproduct materials as aggregate
- Use manufactured aggregates with reduced embodied carbon emissions

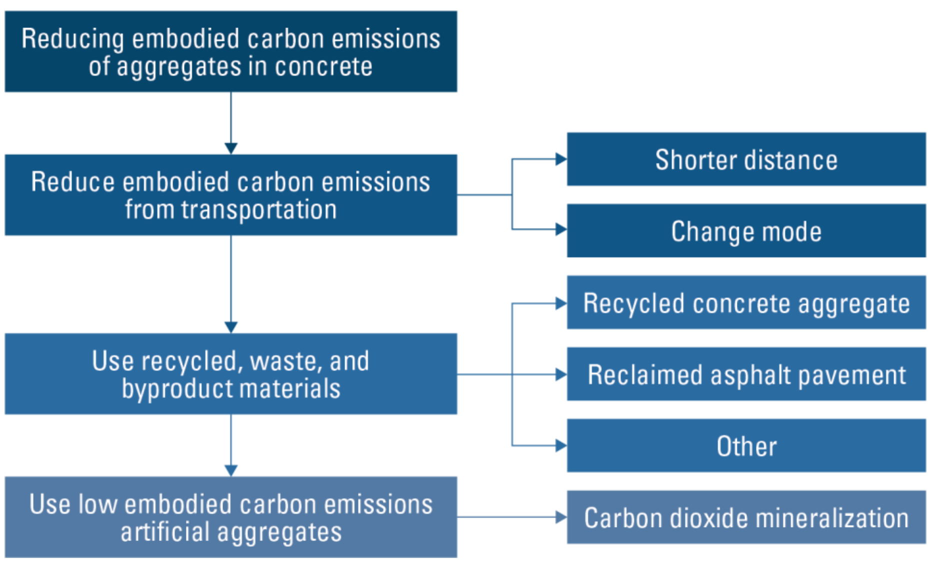


Figure 8. Chart 3: Pathways to reduce embodied carbon emissions of aggregates

Reduce Embodied Carbon Emissions in the Production and Transportation of Aggregates

For every gallon of diesel fuel consumed, approximately 22 lb of embodied carbon emissions are generated. Diesel fuel is consumed predominately by the trucks used to transport materials from the production sites to the concrete plant but also by the heavy equipment (e.g., loaders) that stockpiles the aggregates and transfers the aggregates from the stockpiles to the bins. Further, for mobile concrete plants, electricity is often produced on-site using diesel generators. In combination, the transportation of materials and the use of electricity at concrete plants consume a considerable amount of diesel fuel and are responsible for roughly 4% of the embodied carbon emissions associated with concrete production (Choate 2003).

Aggregates can be moved from the source (i.e., quarry or pit) to the concrete plant using one or more modes of transportation (e.g., truck, rail, or barge). In general, shipping from the source by rail or barge produces fewer embodied carbon emissions per ton-mile of material transported than shipping by truck. Table 1 demonstrates that moving aggregate by rail is over three times more efficient and moving aggregate by inland barge is over four times more efficient than moving aggregate by truck.

Table 1. Estimated national average for freight movement fuel efficiency (diesel) and estimated embodied carbon emissions per ton per mile transported

Mode	Short Ton-Miles/Gallon Consumed	Embodied Carbon Emissions per Short Ton per Mile Travelled (kg CO_2)[a]
Truck[b]	150	0.0679
Rail	478	0.0213
Inland Barge	616	0.0165

Source: Kruse et al. 2012

[a] The embodied carbon emissions per ton per mile were calculated based on one gallon of diesel fuel consumed emitting 22.44 lb (10.18 kg) of CO_2-eq.

[b] Truck load assumed to be 25 tons on a truck with a 40-ton gross vehicle weight, loaded one-way.

Ideally, aggregates would be sourced locally, minimizing the distance to the concrete plant. Aggregates transported long distances should be shipped by rail or barge, if possible, to a nearby distribution point where trucks can then deliver them to the plant. The embodied carbon emissions attributed to the transportation of aggregate are included in concrete facility-specific EPDs, and reductions in embodied carbon emissions related to transportation would be quantified there as part of the overall cradle-to-gate embodied carbon emissions of the concrete. While not often included in concrete facility-specific EPDs, embodied carbon emissions related to the transportation of the concrete from the plant to the project site (i.e., A4) is an optional field and can be considered if the plant is located at a great distance from the project site.

The use of locally available, high-quality aggregates will support the creation of concrete with reduced embodied carbon emissions. If local aggregates are of marginal quality, it may be possible to blend these aggregates with higher quality aggregates shipped some distance to meet goals for reducing embodied carbon emissions without sacrificing workability, strength, or durability. A detailed assessment of the blended aggregates can be conducted to determine the efficacy of this approach in achieving a measurable reduction in embodied carbon emissions without compromising short-term and long-term concrete performance.

Use Recycled, Waste, and Byproduct Materials as Aggregate

The use of recycled, waste, and byproduct materials as aggregate, such as recycled concrete aggregates (RCA) (Cavalline et al. 2022), air-cooled blast furnace slag (Smith 2012), foundry sand, and even reclaimed asphalt pavement (RAP), in lieu of freshly mined and processed natural aggregate should be considered if performance is not compromised. The overall impact of the use of these materials on the embodied carbon emissions of the concrete needs to be assessed on a project-by-project basis because the use of these materials does not in itself ensure that the embodied carbon emissions will be reduced. The reduction in embodied carbon emissions associated with the use of these materials depends on the availability of local natural aggregates, the distance to the aggregate source and the mode of transportation to the concrete plant, and processing requirements. Many economic, environmental, and societal impacts beyond cradle-to-gate embodied carbon emissions make the effective use of recycled, waste, and byproduct materials attractive, and agencies should maximize the use of these materials when possible. For more information on the use of construction and industrial byproduct materials in concrete production, see Cavalline and Sutter (2024) and Cavalline et al. (2024).

Use Manufactured Aggregates with Reduced Embodied Carbon Emissions

An emerging technology that offers the potential for significant reductions in the embodied carbon emissions of aggregates can broadly be characterized as CO_2 mineralization. This technology uses alkaline minerals, often industrial wastes, to permanently sequester CO_2 as part of carbon capture, utilization, and storage (CCUS). The products from CO_2 mineralization can be used as artificial aggregates in concrete production. Several commercial products based on this technology are already on the market. The degree of CO_2 uptake is highly dependent on the alkaline mineral used and the mineralization process, and therefore each product must be characterized individually to accurately assess the impact of this strategy on reducing the embodied carbon emissions of concrete. Further, the quality of these artificial aggregates needs to be characterized to ensure their suitability for long-term use in concrete (Cao et al. 2021).

Strategy 4: Target Mixture Performance Requirements

When proportioning concrete mixtures, the common objective is to determine the most economical and practical combination of readily available materials to produce concrete that will satisfy specification requirements, such as workability (e.g., slump), air content, durability, and strength. To achieve long-term reductions in embodied carbon emissions, however, the requirements for concrete should be broadened through the adoption of performance specifications to include not only the cradle-to-gate embodied carbon emissions at the time of production but also properties more directly linked to the long-term performance of the concrete. The adoption of performance specifications also tends to allow for innovation, which itself can lower the embodied carbon emissions of paving concrete.

The design requirements for paving concrete must comply with agency standards, which must be followed for the agency to approve submitted mixtures. Existing specifications for materials and mixtures that have a proven track record can be used as a starting point in developing agency standards, but prescriptive specifications may contain embedded barriers to reducing embodied carbon emissions that should be reconsidered. Implementing performance specifications can help agencies remove prescriptive requirements from their standards, permitting the development of mixtures with lower embodied carbon emissions that meet or exceed design requirements. Adopting AASHTO R 101, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures, provides agencies with test methods that will allow them to specify what is needed for the concrete mixture to perform well instead of placing restrictions on the mixture that may unnecessarily limit the ability of the mixture designer to reduce embodied carbon emissions.

The approach in AASHTO R 101 reduces reliance on strength alone (especially 28-day strength) as the measure of performance and focuses more broadly on workability, volume stability, and durability. While it is recognized that strength is important, it is also acknowledged that higher strength does not necessarily mean longer lasting, better performing pavements. Further, it is recognized that early-age strength requirements can compromise long-term strength gain and durability. AASHTO R 101 also eliminates prescriptive minimum requirements for cementitious materials content and does not limit SCM replacement levels. Workability tests other than slump are included that can support optimized aggregate grading and lower cementitious contents for paving concrete. Durability requirements, including susceptibility to shrinkage cracking, freeze-thaw durability, and transport properties, are also found in AASHTO R 101.

Figure 9 presents specific pathways in which performance specifications can help reduce the embodied carbon emissions of paving concrete.

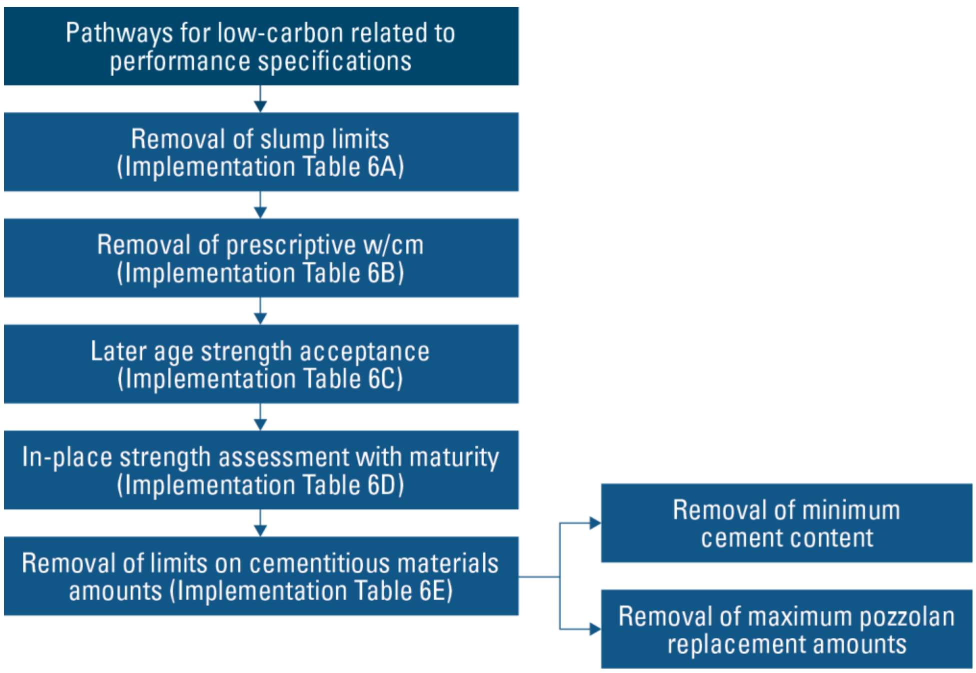


Figure 9. Chart 4: Pathways for reducing embodied carbon emissions related to performance specifications

Embedded within the effort to lower the embodied carbon emissions of concrete mixtures is the opportunity to focus on long-term pavement performance rather than rely on traditional test methods. To this end, current approaches to QC/QA should be examined periodically to ensure that they accomplish 21st century goals. The adoption of performance specifications can help agencies emphasize the concrete properties that matter through specifications and testing while eliminating the less important requirements. This approach to establishing mixture requirements provides options for contractors and producers to find innovative means to achieve engineering goals, including lower embodied carbon emissions. Adopting performance-engineered mixtures (PEM), for example, is a step towards measuring what matters most. Deployed via performance specifications, PEM can lead to innovations in the reduction of embodied carbon emissions.

Strict adherence to standardized testing procedures is important for lowering the embodied carbon emissions of concrete mixtures. The degree to which QC/QA tests are properly performed can significantly impact the proportioning of concrete supplied to a project. For example, contractors and suppliers may respond to variability in testing results by increasing the cementitious materials content of a mixture to ensure compliance with agency specifications. Such a response can impact the degree to which embodied carbon emissions may reasonably be reduced and is an unnecessary restriction on the ability of contractors and suppliers to innovate.

Implementation Table 5A presents ways in which performance specifications can help reduce the embodied carbon emissions of concrete mixtures. Specific changes to performance specification requirements that have the potential to result in concrete with reduced embodied carbon emissions are as follows:

- Removal of slump limits (Implementation Table 5B), because it is known that slump has minimal usefulness for assessing the workability of stiff slipform paving mixtures
- Removal of prescriptive w/cm ratios (Implementation Table 5C), because this concept becomes less meaningful as portland cement is replaced with SCMs at high levels
- Assessment of strength for acceptance at later ages (e.g., 56 or 90 days) (Implementation Table 5D) to accommodate the slower strength gain of concrete made with high levels of SCMs
- Assessment of opening to traffic by use of maturity (Implementation Table 5E) or in-place strength assessment rather than time-based opening criteria.
- Removal of minimum cement contents and maximum pozzolan replacement levels (Implementation Table 5F)

Strategy 5: Consider Other Factors

Other considerations that expand upon the strategies that have already been discussed can impact the embodied carbon emissions of concrete. These considerations lie beyond the traditional scope of current EPDs, which are almost exclusively focused on the Production stage (A1–A3), and therefore fall outside the narrow scope of this guide; however, these considerations are worth noting as opportunities for reducing the embodied carbon emissions of concrete. These considerations may also involve emerging technologies that are potentially important but difficult to categorize. Two of these considerations are discussed below.

Reduce Fuel Consumption in the Production and Transportation of Concrete

In addition to the strategies discussed above, several other strategies are available to reduce the consumption of fossil fuels in concrete production, including the following:

- Optimize plant operations to minimize the need to use diesel-powered heavy equipment to move aggregates once delivered.
- Reduce or eliminate the use of fossil-fuel generators for electricity generation. Instead, install local generators that rely on renewable energy sources and/or ensure that a connection to the electrical grid is available when siting a mobile plant.

Just as the transportation of aggregates to the concrete plant, as discussed under Strategy 3, can significantly impact the cradle-to-gate embodied carbon emissions of concrete, the distance concrete is transported from the concrete plant to the project site is also relevant. However, the embodied carbon emissions associated with the transportation of concrete to the project site are not often captured in a concrete mixture EPD, which includes only A1–A3 and whose scope typically ends at the exit gate of the concrete plant.

Almost universally, concrete is transported from the concrete plant to the project site via truck. Ideally, the concrete plant would be located near the project site, though this is difficult for some rural projects. A close location would minimize the distance travelled and limit the time the concrete is in transit, which can reduce complications in project coordination. Some suppliers have acquired concrete trucks that are powered by compressed natural gas (CNG), which has significantly lower embodied carbon emissions per ton-mile of material transported compared to diesel fuel. The use of biofuels or even hybrid vehicle technologies may also offer reductions in embodied carbon emissions. Although these improvements associated with concrete transportation are of value, they would not be quantified under current EPDs, which largely include only A1–A3. Work is ongoing to incorporate A4 (transportation of concrete from the concrete plant to the project site) into EPDs in cases where its effects on the embodied carbon emissions of concrete are considered impactful (e.g., on rural projects).

Use Calcium Carbonate Mineralization in the Production of Concrete

CO_2 mineralization technology relies on the mineralization of CO_2 and calcium hydroxide into calcium carbonate during the early stages of cement hydration. CO_2 is injected into the concrete during production, either into the concrete drum during primary plant mixing or into the agitating truck after it has been charged with materials. Some of the introduced CO_2 reacts with some of the calcium ions present during the initial phases of cement hydration to form nano-sized particles of calcium carbonate that act as nucleation sites for hydration products. Studies suggest that this can result in increased concrete strength, although in practice the degree to which concrete strength increases is currently not well documented.

In terms of reducing the embodied carbon emissions of concrete, the key advantage to using mineralization during concrete batching and mixing is not that a significant amount of CO_2 is sequestered but that the increased strength of the concrete permits the overall cementitious materials content of the concrete to be reduced, thus achieving the goals described under Strategy 2. SHAs and local agencies should compare optimized mixtures prepared with and without the use of CO_2 mineralization and verify the total reduction in embodied carbon emissions using EPDs to determine the preferred approach.

PART 3: QUANTIFYING

An essential step that an agency can take to reduce the cradle-to-gate embodied carbon emissions of concrete is to select an approach to benchmark the agency's current classes or grades of paving concrete and then use the same approach to assess progress over time.

The preferred tool used by public agencies to assess and understand the embodied carbon emissions of a material is to request an ISO 14025 Type III EPD to obtain environmental impact data, as discussed in the FHWA tech brief entitled *Environmental Product Declarations: Communicating Environmental Impact for Transportation Products* (Rangelov et al. 2021). As stated in that tech brief, "an EPD is a transparent, verified report of the environmental impacts of product manufacturing," including the resources consumed, energy used, and emissions generated. An EPD is produced in accordance with the steps defined by ISO 14025, which entails having a committee of stakeholders develop a product category rule (PCR), developing an LCA from which the EPD is developed, and having the EPD verified and published by a neutral third party or program operator. GWP, which encompasses embodied carbon emissions and is measured in units of kg CO_2-eq/m^3 or kg CO_2-eq/yd^3, is one of many environmental impacts reported in the EPD.

The use of an EPD is required to quantify the potential improvements offered by the strategies presented in this guide. It is important to note that EPDs are developed to reflect a production environment (e.g., the conditions at a concrete plant) as opposed to a laboratory environment, where new mixtures might be evaluated. In the latter scenario, it is not particularly meaningful to produce an EPD. Because EPDs are not universally available, approaches for conducting a preliminary estimate of the cradle-to-gate embodied carbon emissions of a material are summarized below, with an example method provided in Appendix B. These approaches should only be used prior to the development of an EPD.

Using an Environmental Product Declaration

Figure 10 shows an example concrete EPD with typically included information. The reporting shown in this example is in accordance with requirements consistent with a product-specific Type III EPD as defined by the ISO.

ENVIRONMENTAL IMPACTS
Declared Products:
Description:Exterior 4000 PSI
Compressive strength: 4000 PSI at 28 days

Declared Unit: 1 m^3 of concrete

Global Warming Potential (kg CO -eq)	318
Ozone Depletion Potential (kg CFC-11-eq)	7.15E-6
Acidification Potential (kg SO -eq)	0.95
Eutrophication Potential (kg N-eq)	0.24
Photochemical Ozone Creation Potential (kg O -eq)	20.7
Abiotic Depletion, non-fossil (kg Sb-eq)	5.82E-5
Abiotic Depletion, fossil (MJ)	658
Total Waste Disposed (kg)	94.2
Consumption of Freshwater (m^3)	2.40

Product Components: natural aggregate (ASTM C33), Portland cement (ASTM C150), fly ash (ASTM C618), batch water (ASTM C1602), admixture (ASTM C494), admixture (ASTM C260)

Rangelov et al. 2021

Figure 10. Sample information from a concrete EPD

It is important to use either product-specific or facility-specific cement production data as appropriate when developing a concrete EPD. A product-specific EPD represents the environmental impacts of a specific product and manufacturer across multiple facilities (e.g., all AASHTO M 240/ASTM C595 Type IL cement produced by a cement manufacturer), whereas a facility-specific EPD is a product-specific EPD in which the environmental impacts are isolated to a single manufacturer and manufacturing facility (e.g., the AASHTO M 240/ASTM C595 Type IL cement produced at a given cement plant).

Estimating the Embodied Carbon Emissions (Prior to Producing an Environmental Product Declaration)

Because the development of an EPD can require information that might not be available at the time an initial mixture design is developed, a supplier might want to initially use an embodied carbon emissions estimator (examples of which are listed below) to estimate the cradle-to-gate embodied carbon emissions of the concrete while awaiting development of a facility-specific concrete EPD. The use of data specific to the constituent materials will improve the precision of the estimation, especially product-specific and/or facility-specific cement production efficiency data obtained from an EPD. Once again, such estimates should only be used as part of an initial effort to determine potential reductions in embodied carbon emissions. As concrete mixture development continues, an EPD will need to be developed to support the decision-making process.

Tools for estimating the A1–A3 embodied carbon emissions of concrete are readily available online through a variety of entities. These include, but are not limited to, the following:

- National Ready Mixed Concrete Association (https://nrmca.climateearth.com/)
- Slag Cement Association (https://www.slagcement.org/lca-calculator),
- Circular Ecology (https://circularecology.com/concrete-embodied-carbon-footprint-calculator.html)
- WAP Sustainability Consulting (https://thetaepd.com/signup/concrete).

If these tools are utilized for the purposes of estimating the embodied carbon emissions of the Production stage of a paving concrete, ensure that life-cycle stages beyond A1–A3 are not included in the estimation and that the sources of production efficiency data are appropriate.

An alternative approximation methodology is provided in Appendix B.

Regardless of the approach taken, keep in mind that the estimate of the embodied carbon emissions of a newly formulated paving concrete is just that: an estimate. An estimate can help guide the early stages of mixture development, for example, but is insufficient to demonstrate that an actual reduction in embodied carbon emissions has been achieved. Doing so will require the development of an EPD.

GLOSSARY

Carbon Dioxide (CO_2) is a naturally occurring gas and a byproduct of the burning of fossil fuels and biomass, changes in land-use, and other industrial processes. It is the principal anthropogenic greenhouse gas and is the reference gas against which other greenhouse gases are measured. CO_2 therefore has a global warming potential (GWP) of 1.

Carbonation is a process that occurs in concrete where the calcium hydroxide in the concrete reacts with CO_2 in the atmosphere and creates calcium carbonate and water. Carbonation of concrete is a slow and continuous process that permanently sequesters CO_2.

Cradle to Gate (A1–A3) describes the earliest portions of a product's life cycle, from initial material production (e.g., oil exploration and extraction, mining of rock) though product manufacture at the manufacturing site.

Embodied Carbon Emissions (ECEs) are a measure of the cradle-to-gate GWP of a material, expressed in kg CO_2-eq emitted in the production of a defined unit of material. In the case of concrete, embodied carbon emissions are expressed in kg CO_2-eq/m^3 or kg CO_2-eq/yd^3. This measure is estimated from the energy used to extract, process, and transport raw materials as well as the emissions generated from manufacturing processes.

Environmental Product Declarations (EPDs) are transparent, verified reports used to communicate the environmental impacts (e.g., resources used, energy consumed, emissions generated) associated with the manufacture or production of construction materials such as asphalt, cement, asphalt mixtures, concrete mixtures, or steel reinforcement. EPDs are product labels developed by industry in accordance with the International Organization for Standardization (ISO) guidelines set forth in ISO 14025. ISO 14025 includes a critical review process to ensure that the ISO standards and the industry consensus standards described in the product category rule (PCR) document are followed. For more information, see the FHWA tech brief entitled *Environmental Product Declarations: Communicating Environmental Impact for Transportation Products* (Rangelov et al. 2021).

Global Warming Potential (GWP) is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time relative to the emissions of 1 ton of CO_2. This measure was developed to allow comparisons of the global warming impacts of different gases.

Life-Cycle Assessment (LCA), as defined in ISO 14040, is a compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product or system throughout its life cycle.

Life-Cycle Stages represent the various segments in the life cycle of a particular product or more complex system as described in several international standards, including ISO 14040. In the case of pavements, the life-cycle stages typically include the Production stage (A1–A3), Construction stage (A4–A5), Use stage (B1–B7), and End of Life stage (C1–C4).

Modules are used within ISO life-cycle frameworks, including the ISO 14040 framework, to define the components of each life-cycle stage. For example, the Production stage includes A1, Extraction and Upstream Production; A2, Transportation to Manufacturing Facility; and A3, Manufacturing. Combined, the information collected, output generated, and environmental impacts calculated for A1–A3 define the input, output, and environmental impacts of the Production stage.

Supplementary Cementitious Materials (SCMs) commonly include materials such as coal ash (AASHTO M 295/ASTM C618), slag cement (AASHTO M 302/ASTM C989), and natural pozzolans (AASHTO M 295/ASTM C618). Ground glass pozzolan (ASTM C1866) is becoming available in some urban markets. Alternative SCMs that do not meet current standards are entering the market in limited quantities but are expected to increase in availability.

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APPENDIX A. IMPLEMENTATION TABLES

Technology

Implementation Table 1A. Summary of Portland-Limestone Cement

What Is It?

Portland-limestone cement (PLC) is a hydraulic cement meeting the requirements of AASHTO M 240/ASTM C595 Type IL. It has lower embodied carbon emissions than an equivalent AASHTO M 85/ASTM C150 portland cement because additional limestone is interground and/or blended with the clinker during manufacturing. PLCs are engineered to replace AASHTO M 85/ASTM C150 portland cement in nearly all concrete mixtures and can be used with nearly all types of supplementary cementitious materials (SCMs). PLCs have not demonstrated a statistically significant impact on later-age strength or durability compared to similar AASHTO M 85/ASTM C150 portland cement, although early-age characteristics may differ. As is true with any change in cement, concrete properties must be verified through trial batching when using a PLC.

How Does It Work?

PLCs are portland cement clinker blended with a relatively high proportion (between 5% and 15%) of finely ground limestone. The process of manufacturing PLCs requires the cement and limestone to be blended and ground together. This reduces the cement's clinker content, replacing it with limestone and therefore reducing the embodied carbon emissions.

How Does It Impact the Embodied Carbon Emissions of Concrete?

An AASHTO M 240/ASTM C595 Type IL PLC has lower embodied carbon emissions (approximately 8% to 10% lower) than an equivalent AASHTO M 85/ASTM C150 portland cement, as reflected in a cement environmental product declaration (EPD). Concrete made with an AASHTO M 240/ASTM C595 Type IL PLC versus an AASHTO M 85/ASTM C150 portland cement from the same cement plant will therefore have lower embodied carbon emissions, as shown in a concrete EPD, if mixture proportions are held constant.

Recommended Action/Dosage

Replace AASHTO M 85/ASTM C150 portland cement with AASHTO M 240/ASTM C595 Type IL PLC at the same or a lower dosage. Changing the cement type to PLC requires reverifying the concrete mixture properties through trial batching.

Implementation Steps

- Ensure that AASHTO M 240/ASTM C595 Type IL PLC is allowed in cement specifications.
- Allow cement producers to submit AASHTO M 240/ASTM C595 Type IL PLC for inclusion in an approved products list (APL) or qualified products list (QPL).
- Encourage contractors to submit trial batches using AASHTO M 240/ASTM C595 Type IL PLC without increasing cementitious materials content.

Barriers to Implementation

- There is little to no local availability of AASHTO M 240/ASTM C595 Type IL PLC in some areas.
- Most concrete suppliers do not have approved concrete mixture designs using Type IL PLC and will need to generate new mixture designs for acceptance.
- In some applications, construction crews are not familiar with Type IL PLC and the reduced rate of bleed water often associated with the finer grind.
- A lack of familiarity with Type IL PLC results in the use of increased amounts of cement to overcome perceived risks.

Expected Impact on Cost

AASHTO M 240/ASTM C595 Type IL PLC is reported to be priced similarly to conventional AASHTO M 85/ASTM C150 portland cement. Impacts on the construction schedule need to be assessed.

References

FHWA-HRT-23-104; https://www.greenercement.com/

Technology

Implementation Table 1B. Summary of Blended Cements

What Is It?

Blended cements are hydraulic cements meeting the requirements of AASHTO M 240/ASTM C595 Type IL, Type IP, Type IS, or Type IT. Type IL cement is discussed under Implementation Table 1A. Type IP portland-pozzolan cement is a blend of portland cement and up to 40% pozzolans by mass. The pozzolans used can include coal ash, natural pozzolans, or silica fume. Type IS portland-slag cement is a blend of portland cement and up to 95% slag cement. Type IT ternary blended cement is a blend of portland cement and two other constituents, either two supplementary cementitious materials (SCMs) or one SCM and ground limestone. The combination of pozzolan, limestone, and slag can constitute up to 70% of a Type IT cement, with a pozzolan content of no more than 40% by mass and a limestone content of no more than 15% by mass. Blended cements are designed to replace AASHTO M 85/ASTM C150 portland cement and SCMs. Blended cements with higher amounts of SCMs may have slower hydration reactions compared to AASHTO M 85/ASTM C150 portland cement. As is true with any change in cement, concrete properties should be verified through trial batching when using a blended cement.

How Does It Work?

Two silos are commonly used at a concrete plant: one filled with an AASHTO M 85/ASTM C150 portland cement and the other with an SCM. The AASHTO M 85/ASTM C150 portland cement is often selected based on local availability and conditions. For example, sulfate exposure conditions in local soils may require a Type II or Type V cement. The SCMs in the second silo largely reflect local availability and preference and are most commonly coal ash, slag cement, or a natural pozzolan. The cement and SCM(s) are blended at the concrete plant during batching. AASHTO M 240/ASTM C595 blended cements are produced at the cement plant or blending facility, where portland cement is blended with the SCM(s). This allows the cement producer to ensure performance (e.g., balancing calcium sulfate to optimize setting, ensuring sulfate resistance, and so on) and for the concrete supplier to use a cement with lower embodied carbon emissions in one silo as their primary cement source.

How Does It Impact the Embodied Carbon Emissions of Concrete?

As a result of reduced portland cement clinker content, a blended cement has lower embodied carbon emissions than an equivalent AASHTO M 85/ASTM C150 portland cement from the same production facility, as reflected in a cement environmental product declaration (EPD). Concrete made with a blended cement will therefore have lower embodied carbon emissions, as shown in a concrete EPD, if the cement content and other concrete proportions are not changed.

Recommended Action/Dosage

Replace AASHTO M 85/ASTM C150 portland cement with AASHTO M 240/ASTM C595 Type IP, Type IS, or Type IT cement. Changing the cement type to a blended cement requires reverifying the concrete mixture properties through trial batching; verify both fresh and hardened concrete properties.

Implementation Steps

- Ensure that AASHTO M 240/ASTM C595 Type IL, Type IP, Type IS, and Type IT cements are allowed in specifications.
- Allow cement producers to submit AASHTO M 240/ASTM C595 Type IL, Type IP, Type IS, and Type IT cements for inclusion in an approved products list (APL) or qualified products list (QPL).
- Encourage contractors to use AASHTO M 240/ASTM C595 Type IP, Type 1S, and Type IT cements.

Barriers to Implementation

- Slower strength gain may occur and impact the timing of joint sawing, when the pavement can be opened to traffic, and when acceptance testing is conducted, particularly during cooler weather.
- Most concrete suppliers and contractors are not familiar with blended cements and do not have approved concrete mixture designs that include these materials. New mixture designs will need to be developed for acceptance.
- In some applications, construction crews are not familiar with the fact that blended cements often have delayed set and a reduced rate of bleeding, which requires extra diligence when finishing and curing.

Expected Impact on Cost

Blended cements are available in a limited number of US markets and are priced similarly to conventional AASHTO M 85/ASTM C150 portland cement. Impacts on the construction schedule need to be assessed.

References

FHWA-HIF-11-025

Technology

Implementation Table 1C. Summary of Performance Hydraulic Cements

What Is It?

Performance hydraulic cements meet the requirements of ASTM C1157. These cements are designed to meet certain performance criteria based upon testing rather than prescriptive limits. ASTM C1157 specifies six different kinds of performance hydraulic cements: Type GU (general use), Type HE (high-early-strength), Type MS (moderate sulfate resistance), Type HS (high sulfate resistance), Type MH (moderate heat of hydration), and Type LH (low heat of hydration). Performance hydraulic cements are designed to be replacements for AASHTO M 85/ASTM C150 portland cement and often contain supplementary cementitious materials (SCMs). As is true with any change in cement, concrete properties must be verified through trial batching when using a performance hydraulic cement.

How Does It Work?

AASHTO M 85/ASTM C150 portland cements are classified based on their chemical and physical properties and on their ability to meet local conditions, such as sulfate exposure in local soils (i.e., Type I, Type II, or Type V). In comparison, ASTM C1157 performance hydraulic cements are designed to meet certain physical performance requirements of the concrete based on its intended usage. This focus on material performance rather than material composition allows for more innovation in the development of cement blends (i.e., with multiple SCMs and/or limestone) or the potential use of hydraulic binders free of portland cement clinker (e.g., alkali-activated fly ash or slag).

How Does It Impact the Embodied Carbon Emissions of Concrete?

An ASTM C1157 performance hydraulic cement can have lower embodied carbon emissions than the equivalent AASHTO M 85/ASTM C150 portland cement, as shown in a cement environmental product declaration (EPD). The amount of reduction will depend on the type and amount of SCMs (or limestone) used in the cement. The use of binders free of portland cement clinker could result in a significant reduction in the cement's embodied carbon emissions. Concrete made with an ASTM C1157 performance hydraulic cement can have lower embodied carbon emissions, as shown in a concrete EPD, if the cement content is not greatly increased.

Recommended Action/Dosage

Replace AASHTO M 85/ASTM C150 portland cement with ASTM C1157 cement at the cement manufacturer's suggested dosage. Changing the cement type to a performance hydraulic cement requires reverifying the concrete mixture properties through trial batching.

Implementation Steps

- Use demonstration projects to introduce ASTM C1157 cements into the market.
- Review and consider "Optional Physical Requirements" in ASTM C1157 for inclusion in specifications.
- Modify specifications to allow the use of multiple cement types to achieve desired performance outcomes (e.g., lower heat of hydration, high early strength) rather than use prescriptive specifications.
- Develop and implement a testing validation process that allows cement producers to submit ASTM C1157 cements for inclusion in an approved products list (APL) or qualified products list (QPL).
- Consider additional quality control/quality assurance (QC/QA) activities.

Barriers to Implementation

- Certain ASTM C1157 cements are new to the market and may not be available in all areas of the United States or, when available, are generally available in limited quantities.
- Industry lacks experience with specifying performance-based cements.
- The lack of experience in constructing with ASTM C1157 cements will initially increase risks to owners, materials suppliers, and contractors that should be shared among stakeholders.

Expected Impact on Cost

Costs will vary based on cement composition and availability. Initially, costs will be higher for concrete made with ASTM C1157 cements due to the higher material costs and increased level of risk. In time, costs will come into alignment with traditional portland cement for some systems, whereas other systems are likely to always cost more.

References

FHWA-HIF-11-025; CP Tech Center *Integrated Materials and Construction Practices for Concrete Pavement*, 2nd Ed.

Technology

Implementation Table 1D. Summary of Non-hydraulic Inorganic Cements

What Is It?

Non-hydraulic inorganic cements are those that set and harden due to alkali activation, which causes the dissolution of alumino-silica precursors and the initiation of chemical reactions resulting in non-hydrated reaction products. These materials are at times referred to as geopolymers or inorganic polymer cements. The most common alumino-silica precursors include calcined kaolinite clays, low-calcium fly ash, and slag cement. Common alkali activators include sodium hydroxide and sodium silicate solutions of high molarity. These cements often have low embodied carbon emissions and are highly resistant to many durability problems that can affect portland cement-based systems, such as sulfate attack. As novel materials, they are not readily available in the market and may be difficult to work with.

How Does It Work?

Unlike portland cement-based and non-portland cement-based hydraulic cements, non-hydraulic inorganic cements rely on the formation of three-dimensional polymeric alumino-silicate chain and ring structures. The formation of these structures is rapid and occurs when the precursor materials first undergo dissolution in the highly alkali solution created by the alkali activators and then undergo polymerization. The water in the system is included only to facilitate workability and is not part of the reaction products; instead, it is expelled during curing and subsequent drying. The polymerization reaction is sensitive to ambient temperatures. Though conceptually simple, the reactions driving inorganic polymerization are complex and not fully understood. Further, the cements are largely proprietary and have seen only limited use in paving applications.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Non-hydraulic inorganic cements are likely to have lower embodied carbon emissions than AASHTO M 85/ASTM C150 portland cement, depending on the alumino-silica precursor used, as would be shown in an environmental product declaration (EPD). The amount of reduction will depend on the nature of the precursor materials and alkali activator. For some applications, the use of non-hydraulic inorganic cement could result in a significant reduction in the embodied carbon emissions of concrete.

Recommended Action/Dosage

Although some non-hydraulic inorganic cements are available in the United States, for the most part their use has been restricted to specialty applications, and there has been no known use in the United States for a cast-in-place pavement. Further, non-hydraulic inorganic cements are more difficult to work with than portland cement-based systems due to the alkali activator, the sensitivity to temperature, and the general sensitivity of the system to subtle changes in materials or conditions. Current recommendations are to thoroughly test these materials in the laboratory for performance and robustness prior to construction of demonstration projects as a step toward implementation.

Implementation Steps

- Non-hydraulic inorganic cements suitable for large-scale cast-in-place pavement applications are currently in the early stages of development and are not ready for implementation.
- Conduct robust laboratory testing and construct demonstration projects to ensure viability.

Barriers to Implementation

- Non-hydraulic inorganic cement is a new technology with unknown risks related to constructability and long-term performance.
- High-alkali activators must be carefully handled during concrete production.
- A specification framework for specifying these materials has not been developed.

Expected Impact on Cost

Non-hydraulic inorganic cements with lower embodied carbon emissions would be expected to have higher costs than portland cement-based systems. The costs at market introduction would likely be very high, with a reduction in cost occurring as market acceptance increases, though costs will remain relatively high.

References

ACI ITG-10R-18 and ITG-10.1R-18; FHWA-HIF-10-014

Technology

Implementation Table 2A. Summary of Coal Ash

What Is It?

Coal ash (i.e., fly ash and bottom ash) is a supplementary cementitious material (SCM) meeting the requirements of AASHTO M 295/ASTM C618 Class C or F. Class C coal ash has a higher calcium oxide content resulting in both pozzolanic and some cementitious properties, whereas the lower calcium oxide content of Class F coal ash results in predominately pozzolanic properties. Coal ash is a byproduct of coal combustion at electrical generation facilities and is collected either from the exhaust gases (fly ash) or as boiler ash (bottom ash). Fly ash is largely composed of spherical, glassy particles, whereas bottom ash is coarser and more angular. Coal ash can be used in concrete directly after it is collected with little to no processing, or it can be harvested from storage ponds and landfills and processed to make it suitable for use. It can be added to concrete as a constituent in blended cements or at the concrete plant.

How Does It Work?

As a pozzolan, coal fly ash reacts with calcium hydroxide (CH) to form calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH). In addition to having pozzolanic behavior, most Class C coal ash also undergoes hydration reactions when exposed to water. Concrete mixtures with coal ash can exhibit improved workability, lower heat of hydration, and delayed set time. Once set, these mixtures often have slower initial strength gain but higher long-term strength, reduced permeability, and increased resistance to alkali-silica reactivity (ASR) and sulfate attack. Note that some coal ash may result in early concrete mixture stiffening with certain chemical admixtures. The magnitude of these effects depends on the characteristics of the coal ash and the substitution rate (i.e., proper dosage rate), as well as other factors.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Coal ash is commonly used as a partial replacement for AASHTO M 85/ASTM C150 portland cement or AASHTO M 240/ASTM C595 Type IL portland-limestone cement (PLC). A concrete mixture made with coal ash will have lower embodied carbon emissions, as shown in a concrete environmental product declaration (EPD), than the same mixture without coal ash replacement.

Recommended Action/Dosage

Encourage replacement of a portion of AASHTO M 85/ASTM C150 portland cement or AASHTO M 240/ASTM C595 Type IL PLC with coal ash. A typical dosage of Class F coal ash is 15% to 25% by mass of total cementitious material (portland cement + SCM), whereas the typical range for Class C coal ash is 15% to 40%. Use of coal ash requires verifying the concrete mixture properties through trial batching.

Implementation Steps

- The use of coal ash in concrete as a replacement for portland cement has already been fully implemented, although the use of harvested coal ash may require additional considerations. Increasing the replacement rate of portland cement with coal ash will further reduce the embodied carbon emissions of the concrete.
- Ensure that specifications allow and even encourage the use of AASHTO M 295/ASTM C618 Class F and/or C coal ash and consider raising the allowable replacement levels to the maximum typical levels previously discussed.

Barriers to Implementation

- Slower strength gain may impact the timing of joint sawing, when the pavement is opened to traffic, or when acceptance testing is conducted, particularly for construction done during cooler weather.
- The availability of coal ash may be limited in certain markets while the market is transitioning to the use of harvested coal ash.

Expected Impact on Cost

Today, AASHTO M 295/ASTM C618 Class F or C coal ash has a cost similar to that of portland cement. These costs are likely to remain stable in the near future as some markets transition to the use of harvested coal ash.

References

FHWA-HIF-16-001; CP Tech Center *Integrated Materials and Construction Practices for Concrete Pavement*, 2nd Ed.

Technology

Implementation Table 2B. Summary of Natural Pozzolans

What Is It?

Natural pozzolans are supplementary cementitious materials (SCMs) meeting the requirements of AASHTO M 295/ASTM C618 Class N. Class N pozzolans include processed raw materials (e.g., pumicite, volcanic tuffs, opaline cherts), calcined clay, and calcined shale. Calcined materials have been heated to below the temperature of fusion to alter their composition and/or physical state and then ground into a fine powder. Natural pozzolans are added to concrete as a constituent in blended cements or during batching as partial replacement of portland cement. Natural pozzolans offer an alternative to coal ash and slag cement in concrete mixtures. However, a wide range of products are on the market, and not all yield the same effects on concrete mixtures.

How Does It Work?

Natural pozzolans react with calcium hydroxide (CH) to form calcium silicate hydrate (CSH) and calcium aluminate silicate hydrate (CASH) in a concrete mixture. Concrete mixtures that include natural pozzolans can exhibit enhanced strength development, resistance to alkali-silica reactivity (ASR) and sulfate attack, and reduced permeability. Some natural pozzolans (e.g., metakaolin) are used in special applications and can produce concrete with very high strength and very low permeability. Most natural pozzolans act similarly to coal ash, although many have a higher water demand.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Class N pozzolans are generally used to reduce the total amount of AASHTO M 85/ASTM C150 portland cement or AASHTO M 240/ASTM C595 Type IL portland-limestone cement (PLC) in a concrete mixture. A concrete mixture made with a natural pozzolan will have lower embodied carbon emissions, as shown in a concrete environmental product declaration (EPD), than the same mixture without Class N pozzolans. It is noted that the embodied carbon emissions of most natural pozzolans are higher than those of unprocessed coal ash due to the additional mining, processing, and calcining that occurs.

Recommended Action/Dosage

Replace a portion of AASHTO M 85/ASTM C150 portland cement or AASHTO M 240/ASTM C595 Type IL PLC with Class N pozzolan. The range of natural pozzolan dosage in a concrete mixture will vary by type of pozzolan. For example, a typical range for ground pumicite might be 15% to 30% by mass of total cementitious content, whereas this range might be 8% to 12% for metakaolin. The use of a natural pozzolan requires verifying the concrete mixture properties through trial batching.

Implementation Steps

- Ensure that AASHTO M 295/ASTM C618 Class N pozzolans are allowed in specifications.
- Allow producers to submit AASHTO M 240/ASTM C595 Class N natural pozzolans for inclusion in an approved products list (APL) or qualified products list (QPL).
- Support the development of locally available natural pozzolan sources.

Barriers to Implementation

- Some natural pozzolans have a high water demand that must be addressed.
- Slower strength gain may impact the timing of joint sawing, when the pavement is opened to traffic, and when acceptance testing is conducted, particularly for construction done during cooler weather.
- Availability is limited in some regions because the primary natural pozzolan sources are in the western states, although clays suitable for calcining are located throughout the United States.
- Contractors do not have approved concrete mixture designs using natural pozzolans and will need to develop new mixture designs for acceptance.
- Current specifications do not directly assess the pozzolanic activity of the material, allowing some nonreactive materials to be classified as natural pozzolans.

Expected Impact on Cost

AASHTO M 295/ASTM C618 Class N materials typically cost less than portland cement and therefore can be used to reduce the cost of concrete.

References

CP Tech Center *Integrated Materials and Construction Practices for Concrete Pavement*, 2nd Ed.

Technology

Implementation Table 2C. Summary of Slag Cement

What Is It?

Slag cement is a supplementary cementitious material (SCM) meeting the requirements of AASHTO M 302/ASTM C989 and is classified by its reactivity as Grade 80, 100, or 120 (with Grade 120 being the most reactive). Molten slag is a byproduct of producing pig iron from iron ore in a blast furnace. The molten slag is rapidly quenched in a granulator and then ground to a fineness similar to that of portland cement. Slag cement can be used in concrete as a partial replacement of portland cement, as a constituent in blended cements, or as a precursor for alkali-activated cement.

How Does It Work?

Slag cement has hydraulic properties, producing calcium silicate hydrate (CSH) and calcium aluminum silicate hydrate (CASH) in the presence of water. The hydration rate significantly accelerates when calcium hydroxide (CH) is present or if the system pH is increased. Since CH is consumed, slag cement also provides the benefits of a pozzolan. Concrete mixtures containing slag cement can exhibit lower water demand (for the same workability), delayed set time, lower early strengths (especially during cooler temperatures), lower heat of hydration, excellent long-term strength, and improved resistance to chloride ion penetration and sulfate attack. Slag cement can provide resistance to alkali-silica reactivity (ASR) but at a higher replacement level of portland cement compared to Class F fly ash.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Slag cement can replace some of the AASHTO M 85/ASTM C150 portland cement or AASHTO M 240/ASTM C595 Type IL portland-limestone cement (PLC) in concrete, and therefore a concrete mixture made with slag cement will have lower embodied carbon emissions, as shown in a concrete environmental product declaration (EPD), than the same mixture without slag cement. This is true even though the embodied carbon emissions are higher for slag cement than for coal ash due to the energy consumed in granulating and grinding.

Recommended Action/Dosage

Replace a portion of AASHTO M 85/ASTM C150 portland cement or AASHTO M 240/ASTM C595 Type IL PLC with slag cement. A typical slag cement dosage range for a concrete paving mixture is greater than 35% by mass of total cementitious material (portland cement + SCM). The use of slag cement requires verifying the concrete mixture properties through trial batching.

Implementation Steps

- The use of slag cement has been fully implemented in areas of the United States where it is available. Higher replacement rates than those commonly used are possible.
- Ensure that AASHTO M 302/ASTM C989 slag cement is allowed in SCM specifications and provide a pathway for producers to add it to an approved products list (APL) or qualified products list (QPL).

Barriers to Implementation

- Slower strength gain may occur and impact the timing of joint sawing, when the pavement can be opened to traffic, and when acceptance testing is conducted, particularly during cooler weather.
- Late-season placements in northern states where chemical deicers are used can be problematic due to an increased risk of scaling.
- Availability is limited in some regions because slag cement is typically available near iron blast furnaces (which are becoming fewer in number) or near the coasts where it can be imported.
- Many concrete suppliers and contractors do not have experience with concrete made with slag cement.

Expected Impact on Cost

Concrete mixtures that include AASHTO M 302/ASTM C989 slag cement as a replacement for portland cement typically have a cost similar to that of concrete mixtures made only with portland cement (assuming the same total cement content).

References

FHWA-HIF-11-025; CP Tech Center *Integrated Materials and Construction Practices for Concrete Pavement*, 2nd Ed.

Technology

Implementation Table 2D. Summary of Ground Glass Pozzolan

What Is It?

Ground glass pozzolan is a pozzolan meeting the requirements of ASTM C1866. Waste glass from containers and windows, among other sources, are cleaned and finely ground to create a suitable pozzolan. As is true with any change in supplementary cementitious materials (SCMs), the concrete properties must be verified through trial batching when using a ground glass pozzolan.

How Does It Work?

Ground glass pozzolans are composed of about 60% to 70% amorphous silica oxide, while Class F coal ash is typically composed of about 50% to 60% silica oxide. Ground glass pozzolans undergo pozzolanic reactions in a concrete mixture and have a reactivity similar to that of other commonly used SCMs, although the high level of angularity increases water demand.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Environmental product declarations (EPDs) have shown ground glass pozzolans have approximately 5% of the embodied carbon emissions of portland cement. As a result, a concrete mixture with 40% ground glass replacement of portland cement would have approximately 35% lower embodied carbon emissions compared to a similarly proportioned concrete made exclusively with portland cement as the binder.

Recommended Action/Dosage

Replace AASHTO M 85/ASTM C150 portland cement or AASHTO M 240/ASTM C595 Type IL portland-limestone cement (PLC) with 10% to 40% of ASTM C1866 ground glass pozzolan. Changing the SCM to a ground glass pozzolan requires verifying the concrete mixture properties through trial batching.

Implementation Steps

- Ensure that ASTM C1866 ground glass pozzolans can be used to effectively mitigate the alkali-silica reactivity (ASR) of locally available aggregates.
- Ensure that ASTM C1866 ground glass pozzolans are allowed in specifications.
- Allow producers to submit ASTM C1886 ground glass pozzolans for inclusion in an approved products list (APL) or qualified products list (QPL).
- Support the development of locally available ASTM C1866 ground glass pozzolans sources. These are often only viable for relatively small production in metropolitan areas, where a viable source of recycled glass is available.

Barriers to Implementation

- Ground glass pozzolans may not be suitable for mitigating alkali-silica reactivity when used with some aggregates. This must be evaluated as part of concrete mixture acceptance.
- Potential supplies of ground glass pozzolans are relatively small and confined to large urban areas.
- Water demand can significantly increase when ground glass pozzolans are used, requiring the use of a high-range water reducer.

Expected Impact on Cost

Ground glass pozzolans are relatively new to the market, and, as demand increases, costs will decrease as the economic viability of ground glass pozzolan processing plants allow for greater market penetration and availability in smaller markets.

References

ASTM 1866, Standard Specification for Ground-Glass Pozzolan for Use in Concrete; Kaminsky et al. 2020

Technology

Implementation Table 2E. Summary of Alternative Supplementary Cementitious Materials

What Is It?

Alternative supplementary cementitious materials (ASCMs) are supplementary cementitious materials (SCMs) that do not meet the requirements of an existing SCM specification but instead are evaluated using ASTM C1709, which is a guide for the evaluation of ASCMs. This guide provides an approach for conducting a comprehensive evaluation to assess whether a material that has no significant record of performance in concrete can demonstrate promise as an SCM. This evaluation is a first step for new materials and should precede the use of the materials in demonstration projects to further assess their performance.

ASCMs represent a broad category of materials that may be natural, synthetic, or a combination of the two. They might be sourced from waste generated by another industry or purposefully produced as an ASCM for concrete. ASCMs that are currently entering the market include synthetic fly ash, blended materials designed to undergo carbonation while in service, and materials produced through the sequestration of CO_2. Other materials are emerging.

How Does It Work?

An ASCM would need to supplement the hydration of portland cement in a fashion similar to that of a pozzolan or slag cement or through some other means. In general, an ASCM would need to be able to replace portland cement clinker with a material having lower embodied carbon emissions while supporting the development of hydration products that result in long-term strength and durability.

How Does It Impact the Embodied Carbon Emissions of Concrete?

The embodied carbon emissions of an ASCM would need to be calculated using an acceptable means of estimation. It is unlikely that a product category rule (PCR) would exist for a novel ASCM. Instead, the generic core rules presented in ISO 21930 would need to be used to develop an acceptable environmental product declaration (EPD) for the material that would then be used to assess the reduction in the embodied carbon emissions of the concrete.

Recommended Action/Dosage

Recommendations for use would depend on the ASCM. The dosage must be confirmed through extensive laboratory testing.

Implementation Steps

- A proposed ASCM must be evaluated using ASTM C1709 and judged to satisfactorily meet the properties needed for the project at hand.
- Extensive laboratory testing of the ASCM in concrete would be used to determine suitable mixture proportions, and the embodied carbon emissions would be calculated based on the EPD of the ASCM.
- One or more demonstration projects would be constructed to validate the constructability and performance of the ASCM in concrete.

Barriers to Implementation

- The risk of adopting a novel ASCM is high. How the risk will be borne must be agreed upon by all stakeholders to advance implementation.
- ASCMs must be scalable and integrate with existing concrete construction technologies.

Expected Impact on Cost

The costs of using an ASTM are unknown, but the costs cannot be so high as to precluded routine use of the ASCM.

References

ASTM C1709, Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete

Technology

Implementation Table 3. Optimized Aggregate Grading

What Is It?

Optimized aggregate grading considers the combined aggregate particle size distribution in a concrete mixture in lieu of focusing solely on the gradation of source aggregates. When the aggregate grading is optimized, a minimum amount of paste is needed to fill the void space that exists between the aggregate particles, just enough to separate the particles slightly and act as a lubricant to ensure mixture workability. In this way, the paste volume can be reduced while workability and performance are improved.

How Does It Work?

Using a tool such as the Tarantula Curve, the percent retained on each standard sieve size for the combined aggregate particle size distribution is optimized to fall within the recommended limits (see Figure 7). Additional recommendations are made regarding the combined percent of coarse sand (#8 through #30 sieve) and fine sand (#30 through #200 sieve) for slipform paving concrete to ensure workability. The general mixture design strategy is to optimize the combined grading of quality aggregates as discussed. Next, the cementitious materials are selected to create a durable paste with low embodied carbon emissions that meets engineering needs. The final step is to select the paste volume needed to both fill the voids in the aggregate system and provide workability. Spreadsheet tools are available in the references in this table to facilitate this process.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Embodied carbon emissions are reduced by reducing the overall volume of cementitious materials. Cementitious materials containing portland cement have higher embodied carbon emissions than aggregates for a given volume. Therefore, replacing cementitious materials with aggregates will reduce the embodied carbon emissions of the concrete, assuming all other components are held equal. A mixture-specific environmental product declaration (EPD) will demonstrate this reduction in embodied carbon emissions.

Recommended Action

Specifications for slipform paving should be reviewed and, if needed, modified to allow optimized aggregate grading. Application of the guidance provided in AASHTO R 101 regarding the development of concrete mixture proportions should be followed.

Implementation Steps

- Ensure that specifications allow the use of combined aggregate grading and optimization.
- Ensure that specifications do not set requirements for minimum cementitious materials content that are above what is appropriate for the application and climatic conditions. Some state highway agencies (SHAs) have set minimum cementitious materials contents for slipform paving concrete with optimized aggregate grading as low as 470 lb/yd^3.
- In time, incentivize and then require the use of optimized aggregate grading with reduced cementitious materials contents for paving concrete.

Barriers to Implementation

- Many agencies have set requirements for minimum cementitious materials content that are unnecessarily high and create a barrier to reducing embodied carbon emissions.
- Optimized aggregate grading often requires three or more aggregate sources, requiring some concrete producers to obtain additional bins. In urban areas with space limitations, stockpiling additional aggregates may not be feasible.
- The lack of familiarity with proportioning concrete that features optimized aggregate grading and a reduced total cementitious materials content will need to be overcome.

Expected Impact on Cost

Initially, a small increase in cost would be likely as this strategy is introduced into locations where it is not current practice. In time, it will become cost-neutral or will even reduce cost of in-place concrete.

References

FHWA-HIF-15-019; https://cptechcenter.org/mix-proportioning/; http://www.tarantulacurve.com/recommended-specification.html

Technology

Implementation Table 4. Aggregate Pathways to Reduce the Embodied Carbon Emissions of Concrete

What Is It?

Although aggregates have relatively low embodied carbon emissions, they are the largest component in concrete and therefore impact the overall embodied carbon emissions of concrete. The main pathways for reducing the embodied carbon emissions of aggregates are to reduce the embodied carbon emissions associated with transportation; use recycled, waste, and byproduct materials in lieu of natural aggregate where it makes sense to do so; and use artificial aggregates with low embodied carbon emissions as they become available.

How Does It Work?

Although the embodied carbon emissions of natural aggregates are relatively low, the shear mass of aggregates used in concrete production means that their impact needs to be considered. Aggregates are often transported from their source to the point of concrete production by truck, which is the least efficient and most carbon-intensive means of moving materials. If possible, the distance between the aggregate source and the concrete plant should be minimized, and alternative, more efficient modes of transportation, such as rail and barge, should be used to ship aggregates over longer distances. The use of recycled, waste, and byproduct materials as aggregates can also reduce the embodied carbon emissions of concrete, although the impact needs to be assessed at the project level. Finally, the emergence of artificial aggregates with low to negative embodied carbon emissions that are produced through carbon capture, utilization, and storage (CCUS) may offer opportunities for further reductions in embodied carbon emissions in the future.

How Does It Impact the Embodied Carbon Emissions of Concrete

Embodied carbon emissions are reduced by replacing aggregates that have relatively high embodied carbon emissions with aggregates that have lower embodied carbon emissions, as shown in an environmental product declaration (EPD). The assessment is done at the concrete plant and reflects the embodied carbon emissions incurred due to shipping; the use of recycled, waste, and byproduct materials; and the use of artificial aggregates with low embodied carbon emissions. A mixture-specific EPD will demonstrate this reduction in embodied carbon emissions for A2. Note that an EPD typically does not include A4, which covers transportation of the concrete from the plant to the site. If the distance is large, this module should also be considered.

Recommended Action

Specifications for slipform paving should be reviewed to ensure that barriers to the use of quality recycled, waste, and byproduct aggregate materials, as well as artificial aggregates, are removed. Incentivizing the use of concrete with reduced embodied carbon emissions, validated through an EPD, will facilitate a reduction in transportation-related emissions.

Implementation Steps

- Incentivize the use of concrete with low embodied carbon emissions as validated through an EPD.
- Ensure that specifications allow the use of quality recycled, waste, and byproduct materials, as well as artificial aggregates.
- Conduct demonstration projects with concrete made from quality recycled, waste, and byproduct aggregate materials, as well as artificial aggregates, as they become available.

Barriers to Implementation

- Local availability of quality aggregates is lacking in some areas, and the ability to change the mode of aggregate transportation may be limited in some markets.
- The lack of familiarity with concrete made from recycled, waste, and byproduct aggregate materials will need to be overcome.
- Specifications may include barriers to implementation that need to be evaluated.
- The supply of artificial aggregates is lacking and their quality is uncertain.

Expected Impact on Cost

Initially, a small increase in cost would be likely as this strategy is introduced into locations where it is not current practice. In time, it will become cost-neutral or even reduce the cost of in-place concrete.

References

CP Tech Center *Recycling Concrete Pavement Materials: A Practitioner's Reference Guide*; FHWA-HIF-22-020

Technology

Implementation Table 5A. Use of Performance Specifications to Reduce the Embodied Carbon Emissions of the Concrete Mixture

What Is It?

Traditional concrete specifications are predominantly prescriptive, meaning that the specifications explicitly identify the materials to be used on the project (e.g., cement type, minimum cementitious materials content, minimum w/cm ratio) as well as acceptance criteria. Further, traditional specifications rely on a limited number of test methods (e.g., slump, total air content, strength) that generally have little direct correlation to future performance. These specifications have been adequate in the past but tend to limit innovation by making it difficult to introduce new material technologies. Performance specifications, in contrast, define the functional requirements for the project (e.g., in terms of structural capacity or durability) and use performance measures that are more directly linked to in-service performance, such as cracking tendency and permeability.

How Does It Work?

The American Association of State Highway and Transportation Officials (AASHTO) recently adopted AASHTO R 101, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures. Agencies can use this standard for guidance in adopting performance specifications by considering the properties of concrete directly linked to workability and long-term performance. Though the standard was developed for paving mixtures, elements can be adopted for use with other classes of concrete with few to no changes. This versatility has been demonstrated by early adopters of the standard.

How Does It Impact the Embodied Carbon Emissions of Concrete?

The adoption of performance specifications opens the door to further reductions in embodied carbon emissions by eliminating barriers to innovation that exist in prescriptive specifications. This allows consideration of innovative concrete materials with lower embodied carbon emissions that otherwise could not be considered. Quantifying the benefits of these materials would rely on generation of an environmental product declaration (EPD).

Recommended Action

Agencies should review their specifications in consideration of the guidance presented in AASHTO R 101 and other performance specifications. Incremental changes should be made to specifications to support the adoption of performance specifications and performance measures in the long term.

Implementation Steps

- Review existing specifications and incrementally add performance specifications and associated performance measures.
- Ensure that specifications allow a broad range of cementitious binders, significantly reduce or eliminate minimum cementitious materials content requirements, and encourage the adoption of optimized aggregate grading.
- Move away from strength (often used as a surrogate for durability) as the sole acceptance criterion and instead look to performance measures linked to durability and long-term service life.
- Introduce reduced embodied carbon emissions as a goal of mixture proportioning.

Barriers to Implementation

- Agencies need to be educated on performance specifications and performance measurements.
- Suppliers may be resistant to change if they perceive that risk is being shifted onto them. Risk must be borne by all stakeholders to advance implementation.
- Testing laboratories will need to acquire the equipment and qualifications needed to conduct testing that is not currently their standard practice.

Expected Impact on Cost

Initially, an increase in cost would be likely as local suppliers and testing firms acquire additional equipment and skills. In time, this strategy will likely become cost-neutral.

References

AASHTO R 101, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures

Technology

Implementation Table 5B. Removal of Slump Limits

What Is It?

Slump is the most commonly used parameter to assess the consistency of concrete, even though it is known to have significant limitations for the assessment of stiff paving concrete. A test method for assessing slump was adopted in 1922 by the American Society for Testing and Materials (now called ASTM International) as ASTM C123. ASTM C123 was an appropriate test to use at a time when concrete consisted solely of portland cement, aggregates, and water because, in this scenario, its results correlate directly to the amount of water introduced into the mixture if the other mixture constituents remain the same. Today's concrete, however, often contains multiple admixtures and supplementary cementitious materials (SCMs) that can strongly influence the slump without changing the water content in the mixture. While slump remains an appropriate tool for assessing batch-to-batch uniformity, it no longer provides insight into the quality of paving concrete and therefore should not be used as an acceptance test, especially because it does not account for the effect of vibration.

How Does It Work?

To measure slump, concrete is placed and consolidated in three layers in a 12 in. high cone having an 8 in. diameter base and 4 in. diameter open top. After the top is leveled, the cone is carefully lifted vertically, allowing the unsupported concrete to undergo subsidence. The decrease in height is measured at the center point to the nearest 0.25 in. and reported as the slump. The slump is widely considered to be a measure of batch-to-batch consistency.

How Does It Impact the Embodied Carbon Emissions of Concrete?

The removal of slump limits reflects the fact that slump is not a reliable performance measure for paving concrete. It is known that concrete having a slump outside of the typically specified limits can be paved reliably and that concrete that is within specified slump limits does not necessarily possess the workability needed for slipform paving. Rejecting concrete based on slump alone is potentially wasteful and can increase the embodied carbon emissions of a project. Ultimately, contractors should be able to choose workability measures that ensure that the finished concrete meets elevation, consolidation, strength, and durability requirements.

Recommended Action

Agencies should review their specifications and remove slump requirements for paving concrete. Slump requirements should be replaced with performance requirements on the finished concrete pavement that focus on meeting elevation, consolidation, strength, and durability criteria. Requiring alternative measures of workability assessment during mixture proportioning, such as the Vibrating Kelly Ball (VKelly) Test (AASHTO T 403) or Box Test (AASHTO TP 137), should be considered.

Implementation Steps

- Evaluate specifications for concrete paving materials and quality control/quality assurance (QC/QA) testing during pavement construction to determine how slump is used to reject concrete as delivered.
- On a trial basis, use special provisions to remove slump requirements and introduce performance requirements on the finished concrete pavement that focus on meeting elevation, consolidation, strength, and durability criteria, as needed.
- Remove slump requirements from specifications.

Barriers to Implementation

Removing a legacy requirement from specifications is difficult. Change will need to be implemented slowly by demonstrating the efficacy of relying on performance requirements instead of slump requirements.

Expected Impact on Cost

This strategy is expected to have little to no impact on cost.

References

FHWA-HIF-2-061

Technology

Implementation Table 5C. Removal of Prescriptive Water-to-Cementitious Materials Ratios

What Is It?

The mass ratio of water-to-cementitious materials (w/cm) is commonly linked to the strength and durability of concrete mixtures, with limits for different exposure conditions routinely found in specifications and codes. A certain amount of water is needed to support cement hydration (typically linked to a w/cm ratio of around 0.40); having a w/cm ratio that is significantly lower than this can result in autogenous shrinkage and cracking. Adding water and increasing the w/cm ratio beyond 0.40 creates void space in the concrete known as capillary porosity. The more water that is added, the greater the volume and interconnectivity of the capillary porosity, which weakens the concrete and makes it more permeable. Concrete designed with the goal of reducing embodied carbon emissions is rarely made solely with portland cement but instead often contains interground limestone as well as one or more SCMs. Further, some alternative cementitious materials systems may not have any portland cement at all. These differences in chemistry and resulting hydration products fray the linkage between w/cm ratio and strength and transport properties (sometimes referred to as permeability), and it is better to specify the properties of direct interest instead.

How Does It Work?

If w/cm ratio requirements are to be removed, performance measures focusing on strength and transport properties will need to be adopted. Whereas strength is simple to measure, direct measurement of transport properties is more difficult. AASHTO R 101 presents electrical resistivity as a method for measuring transport properties, which can typically be a convenient option. For mixture evaluation, mixtures in which a majority of the binder system (at least 50%) is portland cement can be assessed using surface resistivity in accordance with AASHTO T 358. Mixtures in which less than a majority of the binder system (less than 50%) is portland cement can be assessed using formation factor in accordance with AASHTO T 402. For consistency monitoring during production, all mixtures have the potential to be monitored using surface resistivity (in accordance with AASHTO T 358) and even water content or w/cm ratio (using the Phoenix method) based upon mixture-specific values.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Embodied carbon emissions can be reduced by eliminating waste and by permitting the use of innovative materials and quantities to result in concrete that has reduced embodied carbon emissions and that meets performance specifications but may not pass traditional tests. Quantifying the benefits of this strategy would rely on generation of an environmental product declaration (EPD).

Recommended Action

Adopting the recommendations in AASHTO R 101, establish a specification based on resistivity and measured formation factor rather than w/cm ratio.

Implementation Steps

- Study resistivity and formation factor for current paving mixtures.
- Develop a specification and conduct "shadow tests" on current projects.
- Establish performance models and specifications that link formation factor to durability performance.

Barriers to Implementation

- Agencies will need to adopt resistivity testing if they have not already done so.

Expected Impact on Cost

The initial cost for equipment to measure resistivity is relatively low, and the test is easy to run. Little impact on cost is expected.

References

FHWA-HRT-21-095; FHWA-HRT-13-024

Technology

Implementation Table 5D. Later-Age Strength Assessment

What Is It?

In the pursuit of cementitious systems with low embodied carbon emissions, the amount of portland cement clinker in a given mixture is likely to decrease. In addition, new cementitious materials are likely to be developed that not only have lower embodied carbon emissions but may hydrate differently or develop properties at a different rate than portland cement-based systems. One impact of these innovations is that the development of properties such as strength and permeability may take longer than it does for the systems currently in use. Acceptance testing at later ages, such as at 56 days rather than the 28 days currently used in many specifications, allows time for secondary pozzolanic and other reactions to occur that have a later impact on strength gain.

How Does It Work?

Parameters that influence strength at early ages (even up to 28 days) include w/cm ratio, cement content, supplementary cementitious material (SCM) replacement rate, and hydration rate. Later-age acceptance allows systems with slower hydration rates, lower paste contents, and higher SCM replacement rates time to develop strength.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Later-age acceptance allows for innovations in mixture proportions that can result in materials that have lower cradle-to-gate embodied carbon emissions while still achieving their design properties. Quantifying the benefits of this strategy would rely on generation on an environmental product declaration (EPD).

Recommended Action

Specifications should be modified to base acceptance on testing at 56 days or later.

Implementation Steps

- Develop specification language and/or special provisions that reflect acceptance testing at 56 days or later.

Barriers to Implementation

- Delaying acceptance, and therefore payment, may prove challenging to contractors. Provisional acceptance may be given for lower values at earlier ages if trial batches have demonstrated how the properties of interest will develop over time.

Expected Impact on Cost

Because cementitious materials are typically the costliest component of a concrete mixture, costs will decrease with reduced cementitious materials contents in mixtures.

References

TxDOT Special Provision to Item 421: Hydraulic Cement Concrete

Technology

Implementation Table 5E. Maturity for Early Opening to Traffic

What Is It?

The use of maturity to determine when to open a concrete pavement to traffic can reduce construction time, lower costs, and improve construction zone safety. Allowing maturity to inform decisions regarding early opening to traffic can accelerate project timelines, which benefits both agencies and contractors.

How Does It Work?

The maturity method is a standardized technique (AASHTO T 325/ASTM C1074) used to predict the in-place strength of concrete at early ages (up to 14 days) based on the principle that a concrete's strength is a function of its age and temperature history. These parameters together define the concrete's maturity. In other words, strength develops as cement hydrates, and maturity is a measure of how far hydration has progressed. The method assumes that samples of a given concrete mixture attain equal strengths if they attain equal values of maturity. The American Association of State Highway and Transportation Officials (AASHTO) is publishing a new maturity standard in 2024 (AASHTO T 413) that provides procedures for estimating early opening strengths for concrete pavements solely through the use of a maturity index. Existing agency practices that base opening time on strength can be supplemented with this standard to avoid the need to measure strength via field specimens. The new AASHTO standard differs from AASHTO T 276 and AASHTO T 325 in that the concrete age of interest is early and that testing is designed to address the interpretation of strength data at early ages for determining opening times. As such, this standard should not be used to determine the 28-day strengths of concrete pavements.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Use of the maturity method allows for a realistic estimate of in-place pavement strength and thereby allows agencies to avoid adding cement to accelerate strength development. If new sections of pavement can be loaded with construction or everyday traffic at an earlier age, then closures will be shortened and the impacts of traffic delays will be reduced.

Recommended Action

Develop specification language and/or special provisions that allow the use of maturity for determining opening to traffic.

Implementation Steps

The maturity method is a relatively simple technique to implement in the field. It requires building a calibration curve first and then measuring the maturity of the in-place concrete using data loggers in the field. Steps include the following:

- Develop a strength-maturity relationship for the approved concrete mixture at the plant.
- Determine the temperature history of the in-place concrete and calculate its maturity index.
- Use the strength-maturity relationship and the maturity index to estimate the strength of the in-place concrete.

Barriers to Implementation

- A lack of familiarity with the maturity method and how it can be implemented will need to be overcome.
- The maturity method is perceived to be complex.

Expected Impact on Cost

Where time to opening to traffic is a controlling factor, avoiding the unnecessary addition of cement can significantly reduce the cost of the concrete pavement mixture. In addition, the reduced time needed for construction should reduce costs.

References

FHWA-IF-06-004; FHWA-HIF-19-005; AASHTO T 413, Standard Method of Test for Estimating the Early Opening Strength of Concrete Pavements by Maturity Tests

Technology

Implementation Table 5F. Removal of Minimum Cement Content and Maximum Pozzolan Replacement Amounts

What Is It?

Many specifications impose a minimum binder content, minimum cement content, maximum supplementary cementitious material (SCM) replacement rate, or a combination of these. These limits are often based on previous experience with recipe-based mixture proportions and well-known local materials. However, improved proportioning methodologies and better fresh and hardened concrete assessment techniques, coupled with an expanding range of cementitious materials and admixtures, means that these rules of thumb may no longer be needed and could often be counterproductive.

How Does It Work?

Experience has shown that selection of an optimized aggregate gradation system and an appropriate paste content for workability will generally allow mixtures to be prepared with binder contents lower than current specifications permit. Additionally, newer assessment techniques for workability can help ensure that mixtures are placeable by construction crews. Moving to performance specifications can support the removal of recipe-type provisions.

How Does It Impact the Embodied Carbon Emissions of Concrete?

Reducing the binder content of a mixture without compromising its long-term properties will reduce the embodied carbon emissions of the mixture at the point of delivery.

Recommended Action

Implement specification language that focuses on the performance characteristics of a mixture (e.g., AASHTO R 101) rather than imposing a set recipe.

Implementation Steps

- On a trial basis, use special provisions to remove recipe-type requirements and introduce performance requirements on the finished concrete pavement that focus on meeting elevation, consolidation, strength, and durability criteria, as needed.
- Remove recipe-type requirements from specifications.

Barriers to Implementation

Removing a legacy requirement from specifications is difficult. Change will need to be implemented slowly by demonstrating the efficacy of relying on performance requirements instead of recipe-type requirements.

Expected Impact on Cost

Because cement is typically the costliest component of a concrete mixture, costs will likely decrease with reduced cement contents and maximized SCM replacement rates. Leaner concretes might necessitate an increase in quality control monitoring.

References

Gross et al. 2022

APPENDIX B. EXAMPLE METHOD FOR ESTIMATION OF EMBODIED CARBON EMISSIONS

This appendix describes an approach for estimating embodied carbon emissions that can provide an initial indication of the potential reduction in embodied carbon emissions afforded by implementing one or more of the strategies within this guide. Note that the values in the Production Efficiency and Transportation Efficiency columns of Tables B2 and B3, respectively, are current as of 2023 and are subject to change. These values also have associated uncertainty.

If the results of this method are compared to the information in a concrete environmental product declaration (EPD) using the same constituents and transportation inputs, the results will likely differ. This estimation is only to be used to provide an indication of how changes to a mixture might influence its embodied carbon emissions, for example, in a preliminary assessment of material changes designed to reduce the cradle-to-gate embodied carbon emissions of a paving concrete. The information from a concrete EPD verified to conform to the requirements set forth by the International Organization for Standardization (ISO) is needed to conclusively demonstrate the embodied carbon emissions of the material.

This approach for estimating the A1–A3 embodied carbon emissions of concrete relies on three tables, Tables B1 through B3, which are used to facilitate the necessary calculations. Table B1 is used to identify the embodied carbon emissions associated with the Production stage (A1–A3) of each constituent material's life cycle, which are then combined to obtain an estimate of the total cradle-to-gate embodied carbon emissions for the concrete. Table B2 is used to calculate the embodied carbon emissions associated with A1, and Table B3 is used to calculate the embodied carbon emissions associated with A2. The embodied carbon emissions associated with A3 in Table B1 are estimated to equal 2% of the embodied carbon emissions associated with A1 based on Marceau et al. (2007).

The following steps provide detailed instructions on how to use Tables B1 through B3 to obtain an initial estimation of the embodied carbon emissions of concrete.

Step 1. Determine whether any EPDs are available for any of the constituents to be used in the concrete mixture. If so, input the embodied carbon emissions values indicated in those constituent EPDs into the Production Efficiency column of Table B2. Including the production efficiency information from a product-specific or facility-specific EPD for cement production will significantly increase the precision of this estimation. If an EPD is not available for one or more of the constituents, the values prepopulated in the Production Efficiency column of Table B2 can be used for initial estimation purposes.

Step 2. Input the quantity of constituent materials into the Content column of Table B2 for the specific concrete mixture design based on a total volume of 1 m^3 of concrete.

Step 3. For each row in Table B2, multiply the values in the Production Efficiency and Content columns and report the product in the Material Production column.

Step 4. For each constituent, report the anticipated transportation method to the concrete production facility in the Transportation Method column of Table B2. If multiple transportation methods are expected to be used, input all methods (e.g., Truck, Rail).

Step 5. Report the anticipated transportation distance of the constituents to the concrete production facility in the Transportation Distance column of Table B2. If multiple transportation methods are expected to be used, separate the transportation distances by transportation mode and input all travel distances (e.g., 20 km [truck], 500 km [rail]).

Step 6. Add the values in the Material Production column of Table B2 and report the sum in the A1 column of Table B1.

Step 7. Add the transportation distances in the Transportation Distance column of Table B2 corresponding to each transportation method identified in the Transportation Method column of Table B2. Report the sum of transportation distances for each transportation mode in the appropriate row under the Transportation Distance column of Table B3.

Step 8. Add the constituent weights in the Content column of Table B2 corresponding to each transportation mode identified in the Transportation Method column of Table B2. Report the sum of constituent weights for each transportation mode in the appropriate row under the Constituent Weight column of Table B3.

Step 9. For each row in Table B3, multiply the values in the Transportation Efficiency, Transportation Distance, and Constituent Weight columns and report the product in the Transportation Impacts column.

Step 10. Add the values in the Transportation Impacts column of Table B3 and report the sum in the A2 column of Table B1.

Step 11. Multiply the value in the A1 column of Table B1 by 0.02 (Marceau et al. 2007) and report the value in the A3 column.

Step 12. Add the values in the A1, A2, and A3 columns of Table B1 and report the value in the A1–A3 Total column. The value in the A1–A3 Total column of Table B1 is the estimated embodied carbon emissions.

Table B1. Embodied carbon emissions estimation results

	Life-Cycle Production Stage Module			
Result	**A1**	**A2**	**A3**	**A1–A3 Total**
Embodied Carbon Emissions Estimation (kg of CO_2-eq/m^3 of concrete)				

Table B2. Concrete constituent contents and transportation details

Mixture Design Parameter	Production Efficiency (kg CO_2-eq/metric ton)		Content (metric tons/m³ of concrete)	Material Production (kg CO_2-eq/m³ of concrete)	Transportation Method (Truck, Barge, or Rail)	Transportation Distance (km)
	Value	Validity Dates				
Cement	919[a]					
Portland-Limestone Cement	844[a]					
Blended Cement	739[a]					
SCM (Other than Slag Cement)	50					
SCM (Slag Cement)	147[b]					
Water	0.22[c]					
Fine Aggregate	5.51[d]					
Coarse Aggregate	6.18[d]					
Air-Entraining Admixture	439[e]					
Water-Reducing Admixture / Superplasticizer	1340[e]					
Accelerating Admixture	1230[e]					
Retarding Admixture	1530[e]					

[a] https://www.cement.org/sustainability/pcr-epds
[b] https://www.slagcement.org/epd
[c] https://www.danfoss.com/en/about-danfoss/articles/dhs/the-carbon-footprint-of-potable-water/
[d] https://www.nssga.org/sites/default/files/2021-05/NSSGAGreenhouseGasEmissionsReport04-26-21.pdf
[e] https://www.efca.info/efca-publications/environmental/

Table B3. Transportation details

Transportation Mode	Transportation Efficiency (kg CO_2-eq/km/metric ton)	Transportation Distance (km)	Constituent Weight (metric tons)	Transportation Impacts (kg CO_2-eq/m³ of concrete)
Freight Truck	0.0465[a]			
Barge	0.0146[a]			
Rail	0.0113[a]			

[a] Based on Kruse et al. 2012

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