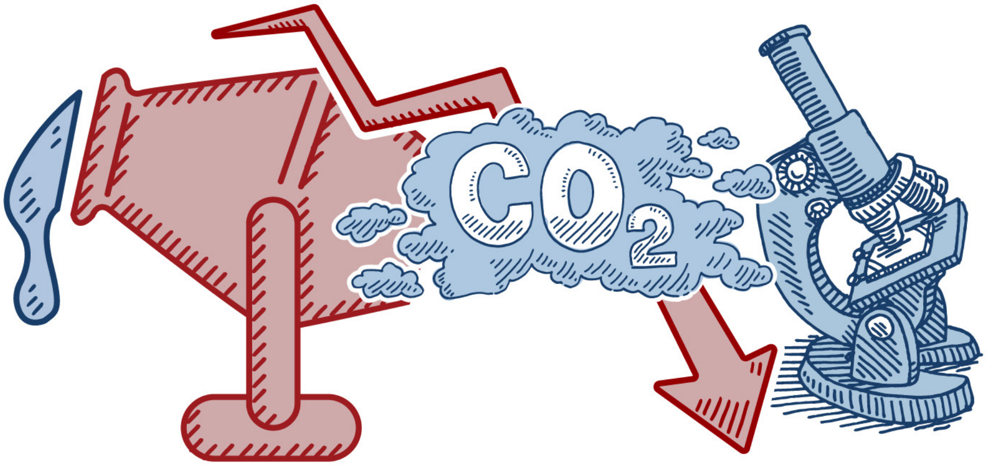

Paving the Way to Innovation:

Moving from Prescriptive to Performance Specifications to Unlock Low-Carbon Cement, Concrete and Asphalt Innovations

CLEARPATH

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Major Contributions

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Role: Report and methodology conceptualization, conducted expert and stakeholder interviews, collected data, conducted all data analysis, and led report writing.

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About CATF: Clean Air Task Force (CATF) is a nonprofit organization working globally to safeguard against the worst impacts of climate change by catalyzing the rapid development and deployment of low-carbon energy and other climate-protecting technologies. With over 25 years of internationally recognized expertise on climate policy and a commitment to exploring all potential solutions, CATF is a pragmatic, non-ideological advocacy group with the bold ideas needed to address climate change. CATF has offices in Boston, Washington, D.C., and Brussels, with staff working remotely around the world.

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Disclaimer

Reviewers and discussants were not asked to concur with the judgments or opinions in this report. All remaining errors are the authors’ responsibility alone.

Executive Summary

The concrete sector currently accounts for roughly eight percent of global emissions.[1] Global annual demand for concrete is expected to grow from 14 billion to 20 billion cubic meters by 2050,[2] due to population increases and urbanization. By sticking with the status quo, this demand growth could increase annual carbon dioxide (CO2) emissions from 2.75 billion tons to 3.8 billion tons worldwide,[3] an increase roughly equivalent to the total U.S. industrial emissions in 2021.[4] This sector represents the building blocks and the glue to all economic growth, so deploying cutting-edge innovations and leveraging low-carbon domestic resources in this sector can deliver safe infrastructure that facilitates growth with lower or zero emissions. This report provides a comprehensive analysis and characterization of types of regulations, known as specifications, governing the use of concrete, cement, and asphalt in public works, and innovative solutions for how American producers can lead the world in lower emissions.

The U.S. is leading the world in the development of innovative low-carbon cement, concrete, and asphalt materials and practices. However, increasing the commercialization and adoption of innovative low-carbon concrete and asphalt mixes and established low-carbon replacements like supplementary cementitious materials (SCMs) and recycled asphalt pavement (RAP) in the public sector faces a key barrier: overly prescriptive specifications.

Prescriptive specifications are preset “recipes” set into law by state agencies, such as the State Department of Transportation (DOT), that producers must follow, and include limits on the type of and proportions of materials, such as SCMs, that producers can use. These specifications are set for individual projects by both state DOTs and often by private project developers. They have traditionally been used because they are relatively easy for the construction industry workforce to follow because of ease of implementation for the workforce but need to be modernized now that developers have access to comprehensive tests, advanced knowledge of construction materials and modern technologies. Unfortunately, by requiring the use of specific types or quantities of materials, prescriptive specifications prohibit using alternative products or practices that can achieve the same performance with a potentially lower cost and lower carbon intensity. Therefore, there is a compelling need to modernize these specifications to commercialize safe, low-carbon concrete and asphalt.

On the contrary to prescriptive specifications, performance specifications have been developed by State DOTs, the Federal Highway Administration (FHWA), industry and specification-setting bodies to modernize specifications and lower barriers to entry for materials with lower emissions.[5] Performance specifications require producers to deliver materials with certain strength, endurance and performance qualities instead of requiring a preset recipe. By adopting performance specifications, both old and new producers have the flexibility to design their products as they see fit and use novel, lower-carbon cement, concrete, and asphalt materials.

This report’s authors documented material standard specifications from each State’s DOT and assessed the prevalence and restrictiveness of these regulations governing the use of concrete, cement, and asphalt in public works. The analysis found that there is at least one type of prescriptive requirement for cement and concrete that exists in every state across the U.S., and that 48 states have some form of prescriptive requirements for asphalt. This analysis sheds light on the extent to which these specifications can potentially support or prevent concrete and asphalt decarbonization and how prevailing prescriptive specifications maintain a status quo that hinders innovation.

Paving the Way to Innovation

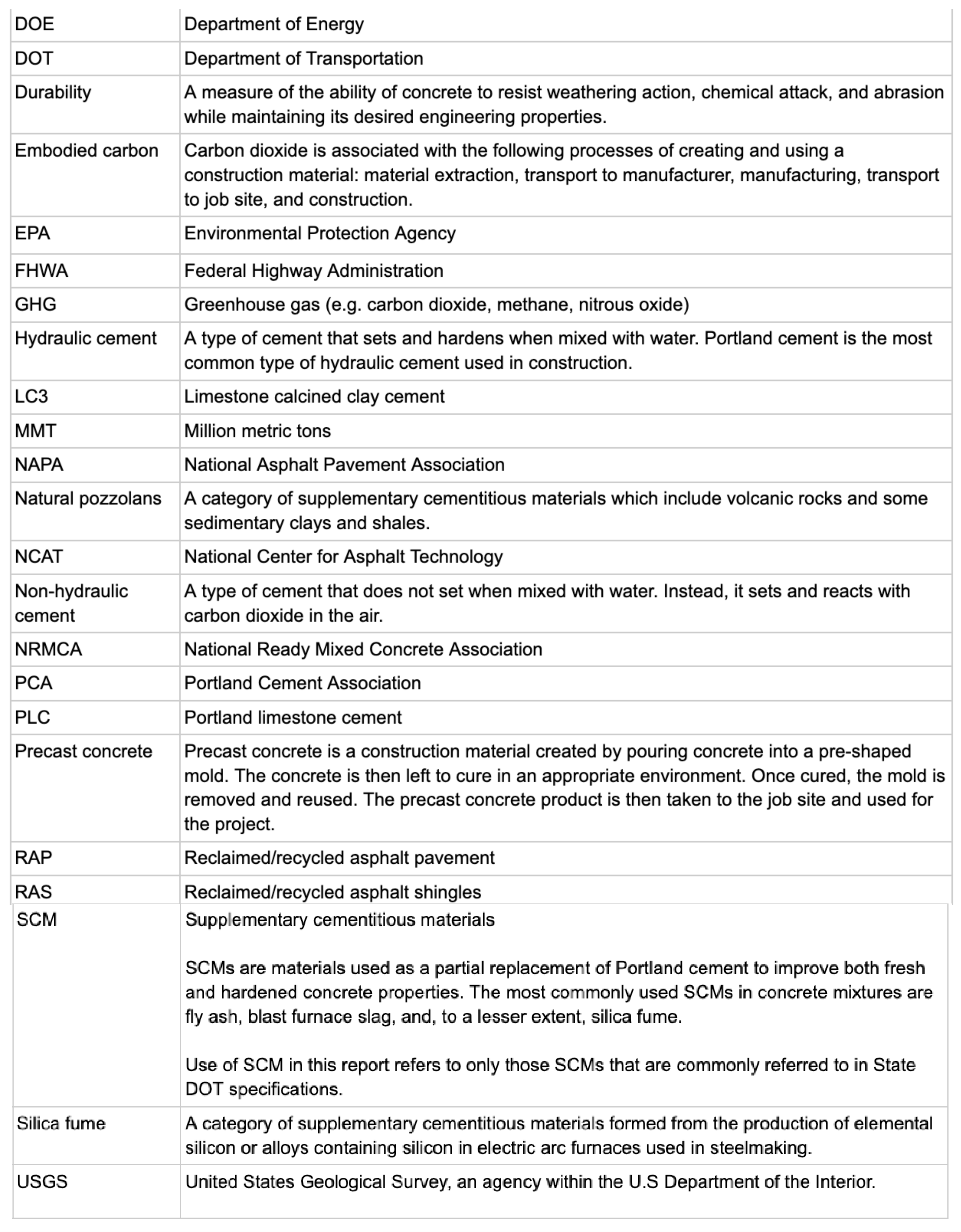
Updating prescriptive specifications towards performance specifications in the U.S. has the potential to unlock emissions reductions and materials savings for producers and taxpayers. As an example, widespread adoption of RAP can avoid 140,000 tons of CO2 emissions annually:[6] the equivalent of 30,500 cars being taken off the road in one year,[7] while increasing SCM usage in concrete reduces emissions by up to 70% relative to concrete made just from Portland cement.[8]

This regulatory change can also help position the U.S. to continue leading the world in developing the low-carbon materials that make up the building blocks of the future. The following three categories of actions can accelerate the adoption of performance specifications:

- **Bolster Technology Validation and Deployment:** The federal government can leverage existing funds to incentivize State DOTs to modernize specifications towards performance specifications and conduct demonstration projects to de-risk the use of new materials. This approach prioritizes safety while providing demand certainty to domestic concrete manufacturers and innovators.
- **Facilitate Workforce Development:** Federal agencies, universities, and industry stakeholders can facilitate education and workforce training and development to accelerate the adoption and implementation of innovative practices and technologies.
- **Streamline Specification Development and Expand Testing Availability:** The U.S. DOT can conduct basic research and development on the performance characteristics of supplementary cementitious materials (SCMs) to update testing and validation for performance specifications.

Glossary

AASHTO	American Association of State Highway and Transportation Officials. AASHTO is a nonprofit, nonpartisan association representing highway and transportation departments in the 50 states, the District of Columbia, and Puerto Rico which publishes specifications, test protocols, and standards. Standards are issued for design, construction of highways and bridges, materials, and many other technical areas.
ACI	American Concrete Institute Authority and resource for the development, dissemination, and adoption of consensus-based standards, technical resources, educational programs, and expertise for individuals and organizations involved in concrete design, construction, and materials.
ASTM	ASTM International, formerly known as the American Society for Testing and Materials An international non-profit that develops and integrates consensus standards.
BMD	Balanced Mix Design was established by the Federal Highway Administration for a process to design asphalt mixtures based on performance testing materials instead of using chemical or volume-based requirements.
Calcination	The process of heating a material, e.g. limestone in the case of Portland cement manufacture, to expel carbon dioxide and produce lime in an easily powdered condition. Calcination is carried out in kilns.
Carbon neutrality	Balancing the CO2 emitted by an activity or production process by removing an equivalent amount of CO2 from the atmosphere through emissions avoidance, reduction, and carbon offsets.
Carbonation	Saturation of a concrete mixture with carbon dioxide to accelerate the concrete's ability to react with CO2, resulting in permanent CO2 storage while enhancing concrete properties like strength and durability.
Cast-in-place concrete	Concrete which is directly poured and cured onsite in the concrete's finished position.
CCUS	Carbon Capture, Utilization, Storage
Cement	A powder that binds together sand, gravel, and water to make concrete. For the purpose of this report, cement refers to Portland cement which is the dominant form of cement manufactured and used today.
Chemical admixture	Chemical admixtures are the ingredients in concrete other than Portland cement, water, and aggregate that are added to the mix immediately before or during mixing. Producers use admixtures primarily to reduce the cost of concrete construction; to modify the properties of hardened concrete; to ensure the quality of concrete during mixing, transporting, placing, and curing; and to overcome certain emergencies during concrete operations.
Clinker	A solid material produced in the manufacture of Portland cement after heating ground limestone and clay in a kiln at 2,600°F. It is an intermediate product that is ground up and mixed with gypsum to produce Portland cement.
CO_2	Carbon dioxide
Compressive strength	A measure of the ability of concrete to withstand loads that will decrease the size of the concrete.
CTAC	Concrete Testing Adherence Collaboration



DOE	Department of Energy
DOT	Department of Transportation
Durability	A measure of the ability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties.
Embodied carbon	Carbon dioxide is associated with the following processes of creating and using a construction material: material extraction, transport to manufacturer, manufacturing, transport to job site, and construction.
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GHG	Greenhouse gas (e.g. carbon dioxide, methane, nitrous oxide)
Hydraulic cement	A type of cement that sets and hardens when mixed with water. Portland cement is the most common type of hydraulic cement used in construction.
LC3	Limestone calcined clay cement
MMT	Million metric tons
NAPA	National Asphalt Pavement Association
Natural pozzolans	A category of supplementary cementitious materials which include volcanic rocks and some sedimentary clays and shales.
NCAT	National Center for Asphalt Technology
Non-hydraulic cement	A type of cement that does not set when mixed with water. Instead, it sets and reacts with carbon dioxide in the air.
NRMCA	National Ready Mixed Concrete Association
PCA	Portland Cement Association
PLC	Portland limestone cement
Precast concrete	Precast concrete is a construction material created by pouring concrete into a pre-shaped mold. The concrete is then left to cure in an appropriate environment. Once cured, the mold is removed and reused. The precast concrete product is then taken to the job site and used for the project.
RAP	Reclaimed/recycled asphalt pavement
RAS	Reclaimed/recycled asphalt shingles
SCM	Supplementary cementitious materials SCMs are materials used as a partial replacement of Portland cement to improve both fresh and hardened concrete properties. The most commonly used SCMs in concrete mixtures are fly ash, blast furnace slag, and, to a lesser extent, silica fume. Use of SCM in this report refers to only those SCMs that are commonly referred to in State DOT specifications.
Silica fume	A category of supplementary cementitious materials formed from the production of elemental silicon or alloys containing silicon in electric arc furnaces used in steelmaking.
USGS	United States Geological Survey, an agency within the U.S Department of the Interior.

Introduction

Concrete and asphalt are two of the most commonly used building materials in the United States. Concrete applications include the construction of buildings, bridges, tunnels, roads, and dams.[9] Asphalt is used for surfacing 84% of U.S. roads, making it the backbone of the U.S. transportation system used to build roads, highways, airport runways, parking lots, driveways and beyond. Cost-effectively reducing emissions from the production and use of these materials delivers clean, reliable and affordable infrastructure that the U.S. relies on.

Commercially available products and widely used practices can yield carbon emissions reductions; examples include optimized mix proportions and project designs, displacing carbon-intensive materials with lower-carbon materials, and recycling concrete and asphalt from prior uses. The adoption of these solutions is stymied by requirements laid out in specifications and standards that determine what type and quantity of asphalt, cement and concrete can be used for different construction projects. Such requirements are often referred to as prescriptive specifications because they establish rules that prescribe or require what, how, and where materials can be used

Performance specifications help drive innovation through competition, and improved performance with lower risk, cost-savings, and emissions reductions. Current regulatory approaches using prescriptive specifications typically require the use of specific types or quantities of materials, preventing the commercialization of innovations that can reduce costs and emissions and blocking producers from optimizing mixtures for performance. In contrast, performance specifications state the desired outcome without explicitly requiring material types or quantities. Since performance specifications are typically set in terms of structural performance and the ability to resist environmental conditions, they incentivize producers to design the most cost-effective mixtures best suited to the application.

The adoption of codes, standards, and specifications that set requirements for the desired performance of concrete, cement, and asphalt can unlock these lower-cost and lower-carbon innovations. U.S. government procurement across federal, state, and local levels accounts for at least 40 percent of all procurement spending on concrete annually.[10] State Departments of Transportation (DOTs) have jurisdiction to set standards and guidelines over cement, concrete, and asphalt used in nearly all types of public works construction. Their authority, as well as their buying power, leads suppliers, end-users, and other market participants to adopt their standards, making these specifications a key lever for enabling greater market access for asphalt, cement, and concrete innovations.

Since State DOTs write their own specifications for construction by drawing on national standards and then make additional modifications, there are 50 different sets of specifications and testing requirements, complicating the process of introducing new materials in public works construction. Also, many concrete mix provisions within state specifications were developed based on concrete technology that predates the use of cement-replacement materials and chemical admixtures. Additionally, State DOTs use standards in specifications to unify approaches regardless of differing end-uses and environments. This one-size-fits-all approach further inhibits innovation.

The body of the report is organized as follows. First, it presents a high-level overview of concrete, cement, and asphalt with regard to their composition, production process, and emissions associated with both. Second, the report covers the background regulatory terms and entities involved for each material. The third section outlines the benefits that the adoption of performance specifications can achieve. Next, the key challenges facing an industry-wide move from prescriptive to performance specifications are covered. This is followed by policy recommendations that can facilitate and accelerate the shifting to performance specifications for asphalt, concrete, and cement.

This report concludes with a snapshot of the current regulatory landscape for concrete, cement, and asphalt specifications across the country. The data was collected and documented from State DOT standard specifications or manuals for construction in order to analyze and assess the prevalence and restrictiveness of these regulations governing the use of concrete, cement, and asphalt in public works. This sheds light on the extent to which these regulations can potentially aid or oppose concrete and asphalt decarbonization. Appendices A and B in this report provide summary statistics and graphics of the existing codes, standards, and specifications in place across the country for concrete, cement and asphalt.

Overview of Cement, Concrete, and Asphalt

Concrete is made by blending cement, aggregates (e.g., sand and gravel), and water. While Portland cement only comprises 10 percent of concrete's mixture by weight,[11] it contributes to almost 80 percent of concrete's carbon dioxide (CO2) emissions.[12] In 2019, the Environmental Protection Agency (EPA) reported that 92 cement plants in the U.S. produced between one to two percent of annual U.S. emissions.[13] Meanwhile, asphalt is produced from aggregates and a binder, which is typically a petroleum by-product called bitumen. In 2019, 0.3% of the total U.S. greenhouse gas (GHG) emissions and 1.3% of industrial emissions were from asphalt.[14] Figure 1 below highlights the relative contribution of concrete and asphalt ingredients to their emissions, as a percentage of concrete and asphalt weight.

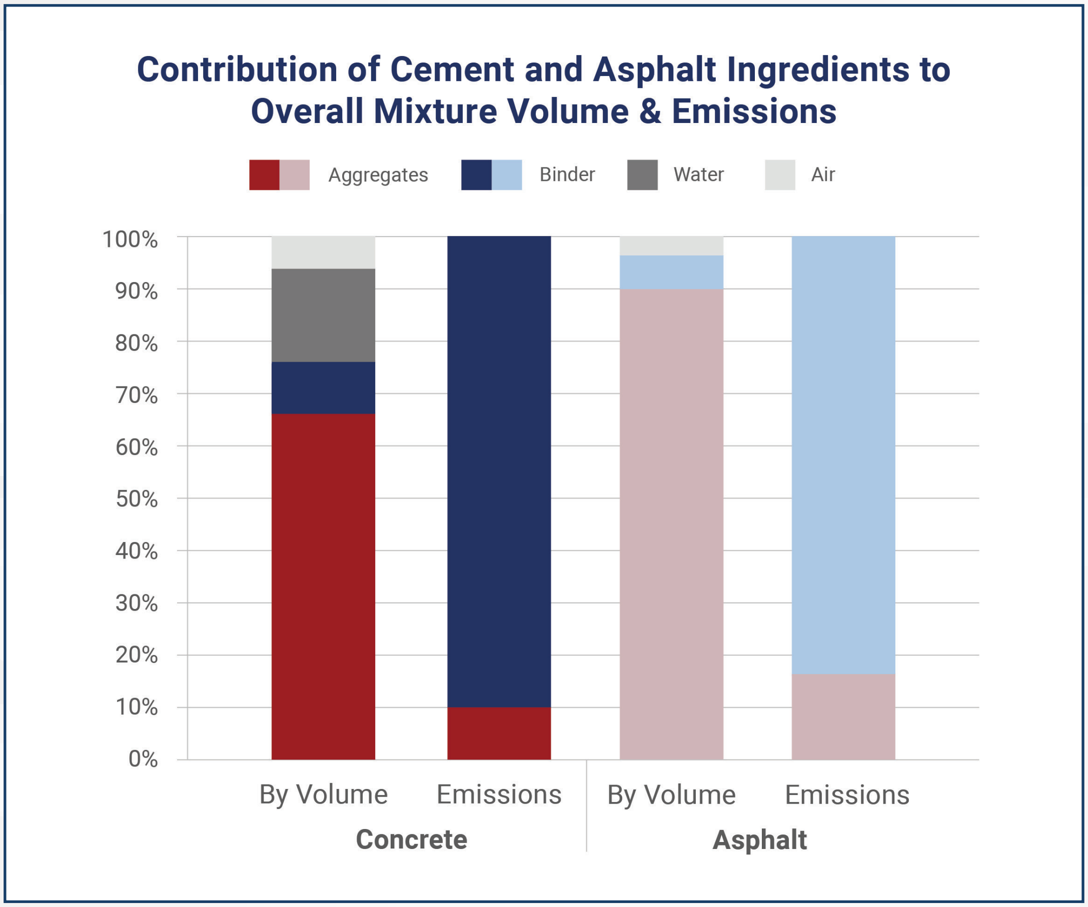


Figure 1: Relative contribution of cement and asphalt ingredients to the overall mixture weight and CO2 emissions for concrete and asphalt, respectively.

Cement's embodied emissions are due to its large production volume and the nature of its production process. Cement manufacturing begins by mining and grinding minerals, mainly limestone, with additives rich in iron, alumina and silica. Those materials are then heated in a kiln, a process known as calcination, creating a product called clinker.[15] A previous ClearPath report on cement and concrete decarbonization found that the carbon released during this process accounts for 60 to 70 percent of carbon dioxide emissions in cement manufacture.[16] That clinker is then ground with gypsum to form cement, which is mixed with water and aggregates to form concrete.[17] Most of the remaining 30 to 40 percent of emissions stem from the use of fossil fuels to heat the kiln to extremely high temperatures.[18]

Cement and Concrete: Background on Codes, Specifications, and Standards

Codes, specifications, and standards are instructions for the design or construction of structures, eligible materials for use, and other matters. They differ in how and who develops them, as well as their applicability, enforcement, and degree of specificity. Codes are instructions to the designer that generally provide minimum requirements intended to ensure safety and durability.[19] For example, a code may require that concrete structures and foundations meet seismic design requirements.[20] Standards and specifications serve to elaborate on the acceptable methods of meeting the code. Codes can include references to standards; standards are generally written with the intent that they become components of model codes.

Codes

Codes provide a set of minimum requirements for public safety and are drafted by code-writing bodies such as the American Concrete Institute (ACI).[21] Codes are legally enforceable once they are adopted by governments: they are absolute and may only be superseded with the permission of the code official for that municipality.[22] Minimum code criteria must be followed regardless of the content of construction contracts, as failure to comply with the code can result in civil or criminal charges. Of note, codes are generally used for buildings and do not apply to pavements, which form the majority of the work that State DOTs conduct.

Standards

Standards are documents that aim to provide uniformity to the processes of construction and contracting. While codes are legally enforceable, standards are widely cited in State DOT specifications to provide minimum material requirements, design, test methods, and best practices for cement, concrete, and asphalt. ACI code documents are often referenced within standard definitions. For example, standards may require certain grades of material that comply with chemical and physical requirements dependent on end uses, or maximum water-cement ratios. They are not legally binding unless adopted by a government or included in a construction contract.[23]

U.S. standards-developing organizations such as ACI, ASTM International (ASTM), and American Association of State Highway and Transportation Officials (AASHTO) produce some of the most widely used standards for cement, concrete, and asphalt in the U.S. Other sets of standards are industry-specific.[24] ASTM standards are reviewed at least every five years and are removed from publication if not updated after eight years.[25]

Specifications

Specifications usually provide additional requirements on key aspects of material composition and performance. Specifications can be developed by standards-developing organizations like AASHTO and ASTM, State DOTs, or private project developers and their licensed design professionals. The most important specifications for the purpose of this report include material specifications that define the required properties of materials using standard test methods that are written by standards organizations and State DOTs. For example, AASHTO M85 is a key material specification for the composition and use of Portland cement,[26] covering 10 different types of Portland cement, and specifications like M85 are developed by continuous collaboration between volunteer state transportation officials who work on different committees.[27]

State DOTs often write independent specifications for road and bridge construction by borrowing from standard specifications and adding their own requirements. They also often create their own material tests, similarly referencing national standards with modifications. In addition to national standards, other major concrete purchasers establish differing specifications unique to their organization; for example, airports have particular specifications for runways based on the aircraft types they receive.[28] There are also project specifications developed by private project developers and their licensed design professionals that are used to define the requirements for a certain construction project.

Asphalt: Background on Specifications and Balanced Mix Design

Asphalt specifications are predominantly set by the State DOT or State Highway Administrations and contain volumetric requirements. Volumetric requirements establish a recipe for producers to comply with by detailing what materials can be used and in what quantities. Common volumetric specifications include minimum virgin asphalt content, air voids, voids filled with asphalt, and voids in mineral aggregate. Additional requirements can include thresholds on recycled materials, requirements for aggregate size, and percentages of aggregate and binder content that must be included.

Balanced Mix Design (BMD) is the term for performance specification in the asphalt industry and encompasses a suite of approaches that specify what performance tests and targets must be met based on the relevant environment and traffic conditions. The National Center for Asphalt Technology (NCAT)[29] tracks State DOT adoption of the four approaches that are described below:

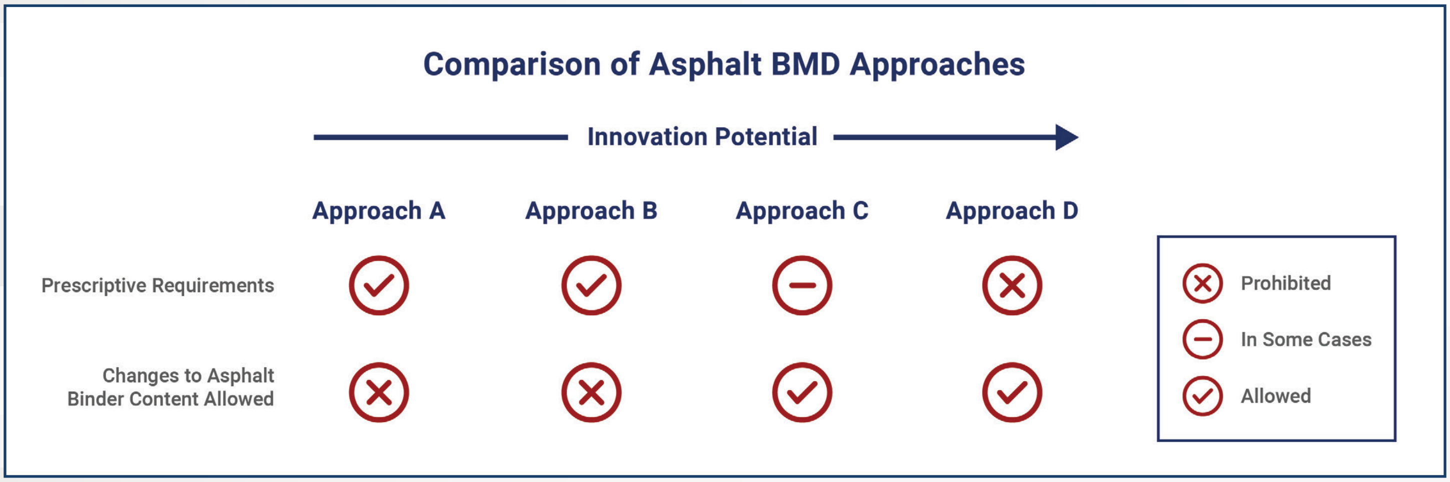
- **Approach A:** Asphalt mixtures must completely fulfill both volumetric requirements and additional performance targets. It is the most conservative approach and often adds compliance complexity, cost, and time and reduces flexibility for asphalt producers.

- **Approach B:** Asphalt mixtures must comply fully with both volumetric requirements in the preliminary stage and additional performance targets. As it does allow minor modifications in asphalt binder content, it is an expanded version of Approach A and has the same regulatory burden for asphalt producers.

- **Approach C:** Asphalt mixtures do not have to meet some or all of the volumetric requirements as long as performance criteria are met. Producers can modify mixes beyond just asphalt binder content, offering more flexibility than approaches A and B.

- **Approach D:** Asphalt mixtures have no volumetric requirements — they only have to meet mixture performance tests. This provides the greatest flexibility for asphalt producers to innovate and reduces their compliance burden.

Appendix B includes NCAT’s map of these approaches across states while Figure 2, below, illustrates how these four approaches incorporate performance requirements and limits on asphalt binder content.



	Approach A	Approach B	Approach C	Approach D
Prescriptive Requirements	✓	✓	⊖	⊗
Changes to Asphalt Binder Content Allowed	⊗	⊗	✓	✓

⊗ Prohibited
⊖ In Some Cases
✓ Allowed

Figure 2: Difference in Balanced Mix Design approaches. For prescriptive requirements, a check indicates inclusion, a cross indicates exclusion and a horizontal bar indicates some prescriptive requirements are included. For asphalt binder content a cross indicates that changes are not allowed while checks indicate that changes are allowed.

Key Takeaways: Cement, Concrete, and Asphalt Specification Analysis

As detailed in Appendices A and B, this report analyzes specifications for cement, concrete, and asphalt use in public works projects across all 50 U.S states. Four key takeaways stand out from the report's findings on the prevalence and stringency of prescriptive specifications:

1. At least one type of prescriptive specification, such as maximum substitution rate for SCMs in concrete, exists for cement and concrete materials and end-uses across each state. This highlights a regulatory status quo that inhibits the development and deployment of innovative materials.
2. Thirty states have at least one example of restricting a material for use, limiting the flexibility for concrete and asphalt producers to optimize mixtures for durability, performance, cost and emissions.
3. Some states have made early progress – 12 states have a form of performance specifications which have provided greater latitude to engineers and/or contractors to comply with construction standards. Notably, Florida, Montana, California, and Maine have explicitly allowed strength testing timelines and thresholds that more adequately evaluated SCMs to be utilized by engineers.
4. Forty-eight states have some form of prescriptive requirements for asphalt: the most common restriction is a maximum substitution rate for recycled asphalt pavement (RAP) in asphalt mixture design.

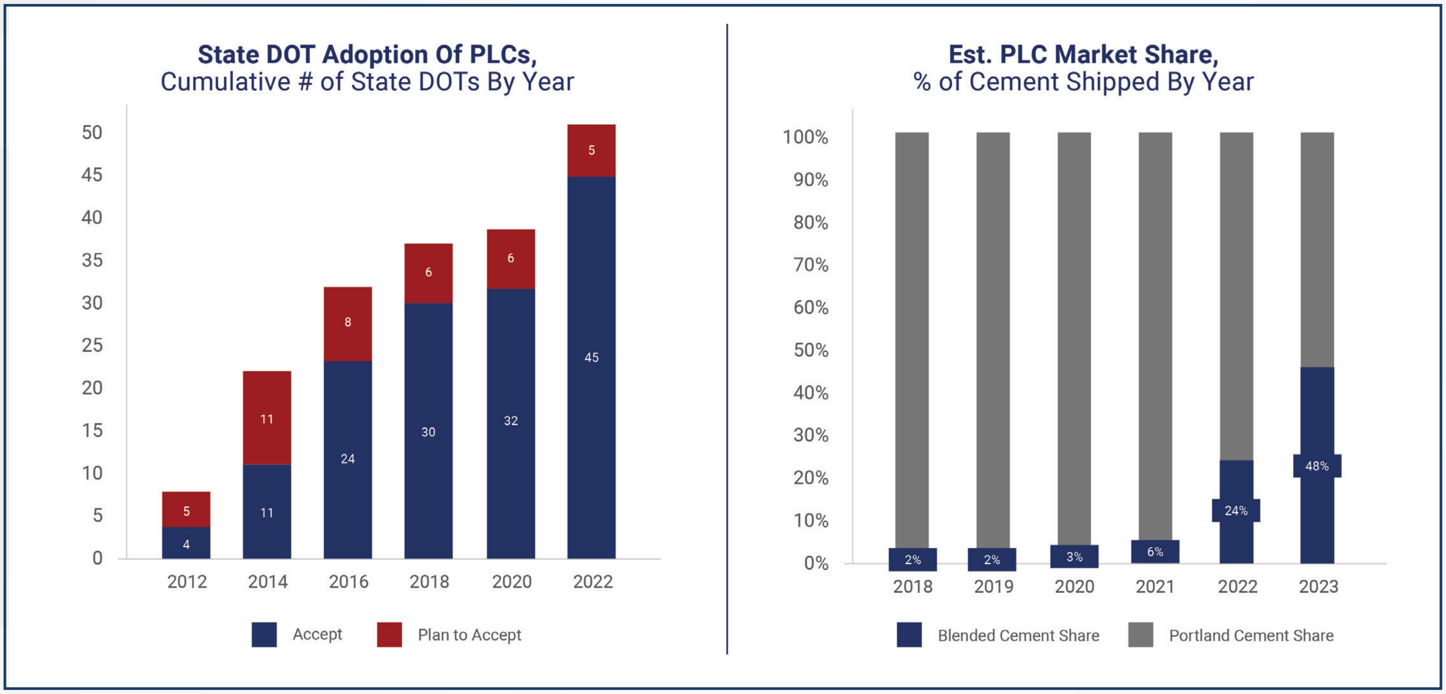
Benefits of Performance Specification and Balanced Mix Design

Performance specification and BMD specify what performance tests and targets must be met based on project needs and environmental conditions. While the use cases, compositions, and particular regulatory framework differ between asphalt and concrete, the two materials share the following benefits from shifting from prescriptive specifications to performance specifications.

Accelerate Commercialization of Innovations

Investment in low-carbon materials must be backed with certainty that enough demand for these products exists to justify changes in highly capital-intensive industries whose commodity products have thin margins. Increased adoption of performance specifications by State DOTs can catalyze the commercialization of low-carbon cement, concrete, and asphalt due to their significant buying power, their position as the default specification setter for a state's market, and the technical validation conveyed by their acceptance of new products or practices.

The catalytic role performance specifications can play in scaling the adoption of low-carbon materials by State DOTs is illustrated by the rollout of Portland limestone cement (PLC), a lower-carbon cement blend, in the U.S. Despite having an established track record with field performance confirmed through use in Europe since the 1960s and Canada since 2008, PLC use did not materially take off in the U.S. until it was first approved under the ASTM C595 standard in 2012. As Figure 3 shows, even with initial standards approval, State DOTs were slow to adopt PLC. Despite significant technological de-risking, it took about five years for half of the U.S states to adopt PLC and a full decade before almost all states had adopted PLC.[30] However, once a majority of states adopted PLC in 2022, uptake accelerated and producers in several regions switched to only producing PLC. Today, PLC now comprises approximately one-third of all cement shipped in the U.S. annually, and its use is growing.[31]


State DOT Adoption Of PLCs,
Cumulative # of State DOTs By Year

Est. PLC Market Share,
% of Cement Shipped By Year

Figure 3: State adoption of PLC and estimated PLC market share on an annual basis.
Credit: Department of Energy Pathways to Commercial Liftoff: Low-Carbon Cement Report, United States Geological Survey Mineral Information Center

Improve Structural Performance and Reduce Risk

Performance specifications and BMD have the potential to deliver infrastructure with improved performance because they base mixture approval on meeting performance parameters and validate these parameters through a range of tests. For concrete, these are compressive strength and durability, and for asphalt, these are stability and resistance. Conversely, prescriptive standards measure the ingredients and not the performance. They use chemical or material parameters to approximate performance which can add complexity while not directly optimizing for the performance.[32]

Increased durability and stability of asphalt mixes can reduce risk once the mixture is laid in the field and can also extend infrastructure life. For example, the Virginia DOT trialed BMD for asphalt mixtures and found that it enhanced pavement density, potentially increasing asphalt pavement service life by 10%.[33] One example of a common concrete prescription is minimum cementitious content limits per unit of concrete that are implemented because cement contributes to concrete strength. However, adding more or less cement than what is necessary can have adverse impacts on performance. A National Ready Mixed Concrete Association (NRMCA) report found that increasing cement content at a given water-cementitious ratio did not result in higher strength but can actually increase shrinkage and related cracking and, therefore, reduce resistance to corrosion.[34] Likewise, not adding enough cementitious material can introduce workability challenges in addition to strength and durability complications.[35]

Prescriptive specifications also hamper the potential contribution of cement replacements, especially SCMs, which are used to replace a portion of Portland cement within concrete mixtures. The two most common SCMs in the U.S. are coal fly ash and blast furnace slag and their contribution to improved performance is hampered by prescriptive requirements. Prescriptive requirements have limited the amount and number of SCMs that can be used, typically at 25-50% of total cementitious material weight, despite their long track record of success.[36] A notable example is the reconstruction of the collapsed I-35W bridge by the Minnesota State DOT. For this project, drilled shafts and footings were built using 60% SCM by weight, while piers were built using 85% SCM by weight, which achieved the desired performance.[37]

Enhance Flexibility and Reduce Compliance Burden

Performance specifications and BMD align risk-sharing with the actors – concrete and asphalt producers – that directly influence the performance of the mixtures. Compliance with performance specifications and BMD empowers producers to use their expertise and local materials to optimize materials and production processes to achieve the desired performance level. This is particularly crucial for concrete because it is not a one-size-fits-all solution: the concrete market is made up of thousands of products made from a range of local materials and designed with different properties and end-users in mind.

Shifting to performance specifications or adopting BMD requires retraining engineers and workers to use performance tests and testing equipment to verify the onsite performance of novel concrete and asphalt materials. This can increase upfront labor, planning, and construction costs and prolong project timelines for first-of-a-kind projects, but with the benefits of reduced maintenance and longer service lifespans. Experiential knowledge gained over multiple projects and a cultural shift toward a deeper understanding of the factors driving concrete and asphalt performance can overcome these challenges over the long term. Additionally, changing the distribution of risk amongst these actors, increasing reliance on end-user expertise, and the availability of testing and validation tools are significant challenges that need to be addressed to realize the full potential of performance specifications and BMD.

Bolster Domestic Supply Chains

Increasing the adoption of performance specifications can expand the use of supplementary cementitious materials (SCMs) and alternative SCMs that are sourced or produced domestically, which can help solve a growing supply chain challenge in two ways. The first is the declining availability of the two most commonly used SCMs. Fly ash, a by-product from coal power generation, has dropped to less than half of its recent maximum in 2008 due to declining coal power generation, and environmental regulations that continue to restrict the use of this by-product.[38] Meanwhile, blast furnace slag production from steelmaking has declined due to shifts away from blast furnace ironmaking methods.[39] Performance specifications can enable producers to use other existing SCMs, such as ground glass, and unlock market access for alternative SCMs. Additionally, alternative SCMs can be sourced locally, thus reducing transportation costs, or may be manufactured in a facility, which benefits from economies of scale and transportation costs when the facilities are closer to end-users.[40] Further, alternative SCMs manufactured in factories have greater predictability and consistency that reduce performance and supply risk. However, alternative SCMs will require the development of standards to ensure compliance with chemical and physical requirements that are particular to different end uses.

The second way performance specifications bolster domestic supply chains is by reducing net import reliance on cement, which has jumped from 14% to 21% between 2018 and 2022.[41] Removing substitution limits on SCMs can reduce cement demand and, by extension, cement imports while strengthening the supply chain for domestic SCMs. While import reliance is not relevant to asphalt, increasing the use of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) in asphalt when it optimizes performance can reduce demand for virgin materials, strengthen sourcing of recycled materials, and send a market signal for innovations.

Long-Term Cost Savings

Shifting to performance specifications and BMD is a long-term cost-saving opportunity for producers, State DOTs, and ultimately taxpayers. Prominently, performance specifications and BMD remove market entry barriers and encourage competition that drives down the cost of supplying materials, final mixes, and completed projects. Second, performance specifications reduce instances when structures and pavements are designed to conform to prescriptive specifications rather than what the life-safety requirements or the environmental conditions the structure is placed in require. Avoiding project over-design reduces the amount of material used, creating savings on material expenses.

For concrete, moving towards performance specifications can enable more precise ordering and usage of cement that avoids adding material above what design specifications require, reducing material costs.[42]

Second, expanding the opportunity for substitute materials with recycled materials and alternative materials, particularly if they could be locally sourced, is a significant opportunity to reduce costs for producers, State DOTs, and taxpayers. A Texas DOT field study highlighted that using a BMD approach in one district reduced per-unit costs of asphalt mixtures by increasing RAP usage. If applied to all of Texas DOT's annual asphalt deployment, this approach could save Texas taxpayers roughly $80 million annually.[43] For concrete and cement, expanding the use of SCMs, which can be between 20-90% cheaper per ton than cement, can save costs for producers, State DOTs, and ultimately taxpayers.[44]

State DOTs and taxpayers experience lifecycle cost-savings for projects built using performance specifications and BMD due to reductions in premature failure and maintenance needs that also extend service life. For example, Maine DOT observed fewer cases of premature failures and estimated that it could save up to $7.5M annually if only 50% of asphalt mixtures in the state were switched to BMD.[45] Similarly, New Jersey DOT observed that using mixtures developed through BMD improved projected pavement lifespans by more than 10 years compared with conventional asphalt and enhanced the overall percentage of road network lanes in good condition from 12% in 2006 to 40% in 2019.[46]

In the near term, BMD and performance specifications may increase project costs and timelines due to increased testing labor and non-material costs, especially for first-of-a-kind projects.[47] However, these approaches can improve the service life of projects, which can partially compensate or potentially lead to savings over the entire lifespan of a project, even with higher upfront costs and construction timelines.[48] Long-term, increasing the adoption of performance specifications and BMD could expand the provision of required equipment and improve labor expertise in testing and using new materials, reducing labor and non-material costs.

Reduce Cement and Concrete GHG Emissions

BMD and performance specification can reduce emissions from asphalt and concrete, respectively, by facilitating the entrance of innovative technologies, reducing maintenance needs, and improving service life. First, BMD increases the use of RAP, which displaces the most carbon-intensive component of asphalt – virgin asphalt binder – without sacrificing safety or durability if tested and applied properly. If the use of RAP in new asphalt increased by one percent nationwide, 140,000 tons of CO2 emissions would be avoided annually:[49] the equivalent of 30,500 cars being taken off the road in one year.[50] Increasing SCM usage in concrete is a crucial emissions reduction lever because it can partially displace the amount of carbon-intensive Portland cement required for a unit of concrete, which reduces emissions by up to 70% relative to concrete made just from Portland cement.[51] These alternative materials also reduce emissions by allowing producers to use locally available materials, thereby reducing transport emissions from procuring out-of-state or imported materials.

Removing market barriers expands the industry's emissions reduction potential by growing the deployment of existing low-carbon materials and creating a path to market for novel cement and concrete mixtures. Performance specifications enable deep emissions reductions by creating markets for innovations involving concrete made from alternative raw materials, Portland cement alternatives, and CO2 curing, which can reduce total emissions by 60 to 100%.[52] An example of concrete produced by CO2 curing is U.S start-up Carbon Built, which uses a cement alternative and cures it with waste CO2 to reduce emissions.[53] Alternatively, another start-up called Sublime Systems has developed a novel process to manufacture an alternative cement that avoids process emissions altogether and was recently certified to comply with ASTM C1157, a performance-based standard.[54] The National Asphalt Pavement Association (NAPA), the leading asphalt industry association, has identified expanded market access for low-carbon innovations as a key strategy to enable the asphalt industry to reach net-zero GHG emissions by 2050.[55]

Finally, optimizing for performance can improve structural durability, avoiding emissions from frequent maintenance cycles or the need to replace infrastructure. It is important to note that under BMD, increasing RAP and RAS usage is not always optimal for achieving a desired level of performance. For example, in some use cases and environments, increased replacement of virgin asphalt binder with RAS can increase premature cracking and aging.[56] Enhanced performance testing is, therefore, an integral element of BMD that ensures mixtures containing RAP and RAS optimize for durability and safety.

Challenges

Despite meaningful strides to shift toward performance specifications, long-standing institutional and industry practices and a lack of trust between parties, products, and technology create challenges. Reluctance to change long-standing practices in the public and private sectors can stem from familiarity with current products and processes that have a long history of success, desire to maintain authority, and a lack of information and guidance for performance specifications. Across the private and public sectors, shifting from prescriptive to performance specifications and BMD will face three interrelated challenges to overcoming inertia and building trust: Workforce Development, Specification Development and Testing Availability, and Technology Validation and Deployment.

Workforce Development

Prescriptive specifications have been used for most of the 20th century; therefore, educating and training the workforce will inherently face a learning curve in shifting to performance specifications. For institutions such as State DOTs, a technical expertise gap will need to be bridged for them to shift to performance specifications and BMD to design mixtures for different infrastructure projects. Safety is of paramount concern for all parties and particularly for State DOTs; changing specification regimes will re-distribute risk and liability to the contracted workforce. State DOTs often forgo implementing a performance specification due to concerns that the local contracting workforce does not have adequate training and equipment to use performance specifications. This is a valid concern, but also a missed opportunity to upskill and incentivize producers and contractors to learn and implement more sophisticated approaches or alternative materials. Based on our landscaping of current specifications at State DOTs, presented in Appendix A, there are currently 12 states that have provided greater latitude to engineers or contractors to comply with construction standards.

Similar proposals have emerged in states like Minnesota, which has established a Value Engineering Incentive that provides guidelines for engineers and contractors to develop alternative compliance proposals as long as they reduce costs without compromising performance.[57]

Specifiers in state DOTs and other companies are also inclined to maintain the status quo because of how they are trained. Risk aversion from the contracted workforce likewise leads to a preference for the status quo and is reinforced through inter-generational training, where younger structural engineers are trained by older engineers to follow legacy specifications that impose greater restrictions on alternative materials. This underscores the importance of enhancing and expanding the education and training ecosystem to connect end-users, regulators, and standards-setting bodies to bridge gaps in knowledge and facilitate the adoption of new materials, approaches, and performance specifications. Examples of institutions at the forefront of research and education are the National Concrete Pavement Technology Center at Iowa State University and the National Center for Asphalt Technology at Auburn University.

Examples of education and training include the U.S. DOT's workshops with State DOTs to assist with starting BMD implementation based on lessons learned by other State DOTs.[58]

Specification Development and Testing Availability

Shifting from prescriptive to performance specifications and BMD will require updating existing specifications and developing new specifications to remove barriers to entry for new products and establish the guidelines to ensure that new products perform as needed. Recent progress includes ASTM approval of the first standards – ASTM C1905[59] and ASTM C1910[60] – for non-hydraulic cement requiring carbonation curing: concrete exposure to carbon dioxide for accelerated hardening and permanent CO2 storage. These standards established specifications and test methods that have unlocked markets for innovative CO2-cured materials used in non-steel reinforced products and can apply to other materials, such as carbonated SCMs. Updates to existing specifications also move these industries towards performance specifications and remove barriers to new materials and innovations. In March 2023, ASTM expanded the definition of coal ash in specification ASTM C618 to enable other types of ash that would otherwise be landfilled to be used in cement, reducing supply chain issues and giving producers greater flexibility in designing a mix that optimizes performance at the lowest costs.[61] For asphalt, the National Cooperative Highway Research Program produced a framework for BMD that State DOTs can consult to assist with shifting to BMD.[62]

The lack of trust in testing results, the development of new tests and specifications, and the availability of equipment for testing and modeling are barriers that contribute to inertia. Overcoming these barriers is critical because increasing the adoption of performance specifications and BMD requires comprehensive testing to ensure the cement and concrete used to provide the required properties for safety and durability. The common practice of over-designing concrete mixtures with cement to ensure conformance with concrete strength limits indicates that contractors hold some degree of distrust with testing.[63] Conversations the authors held with concrete industry experts and stakeholders have identified a certain level of distrust held by contractors with the testing industry to produce accurate results of concrete performance. This will continue to obstruct the use of performance specifications without concerted efforts to adequately train, equip, and certify mixtures created using performance specifications. Finally, a lack of testing and modeling equipment to validate that the performance-based specification fulfills the life-safety requirements for a given construction project is a barrier. This is true for specifiers and especially true for contractors and ready-mix concrete companies that are often resource-constrained small businesses. More efforts like the Federal Highway Administration's (FHWA) equipment loan program for mobile asphalt testing are required to increase testing availability.[64]

Technology Validation and Deployment

Providing technical validation of new technologies and practices is crucial to scaling low-carbon innovation in an industry with significant life-safety risks. Demonstration projects can reduce the technology risk of both performance specifications and low-carbon construction materials by proving out field performance of these early-stage materials and highlighting changes to production techniques and concrete. They can achieve this while imposing minimum risk on the owner, increasing adoption among State DOTs, producers, and contractors who can use real-world data to build confidence in new materials. This lever can also reduce the economic risk of new materials by demonstrating that the materials work well with existing concrete batching and delivery infrastructure, operate as stated in different weather conditions, and do not lead to construction delays. An example the U.S. DOT can build on is the MnROAD Test Facility, jointly operated by Minnesota DOT, FHWA, and National Road Research Alliance, which is testing 12 pavement sections using alternative materials.[65] Another example is NCAT's demonstration study which worked with 41 labs to evaluate the variability of performance tests used in BMD implementation and gain experience using these tests.[66]

The regulatory certainty provided by states and standard-setting board validation and revenue certainty provided by a regulatory structure that provides market access can catalyze private sector investments that further accelerate the commercialization of early-stage companies. The importance of leveraging these dynamics was exemplified in the Department of Energy's (DOE) Pathways to Commercial Liftoff report on low-carbon cement, which highlighted ASTM C1157, a performance specification that creates a signal for novel mixtures and chemistries, as a measure to accelerate emissions reductions in the cement and concrete sector.[67]

Conclusion & Recommendations

Decarbonizing cement, concrete, and asphalt requires a comprehensive approach to address technological, economic and regulatory challenges. Part of this solution is shifting from prescriptive specifications to performance specifications for cement and concrete and to Balanced Mix Design (BMD) for asphalt. These approaches optimize for the performance of concrete, cement, and asphalt infrastructures and, in doing so, unlock opportunities to bring new materials and technologies to market, strengthen supply chains, facilitate workforce development, achieve long-term cost savings, and significantly reduce emissions. Government agencies, such as State Departments of Transportation (DOTs), have significant buying power and establish the specifications for several infrastructure classes, making them important partners and levers to shifting away from prescriptive specifications. Notably, the DOE also determined that meeting 2050 emissions reduction goals requires State DOTs to halve the adoption cycle for new materials from 10 to 20 years to 5 to 10 years and reduce the time between review periods without sacrificing safety.[68]

Policy recommendations to facilitate the shift towards performance specifications and BMD and address the three key challenge areas identified in this report are below.

Facilitate Workforce Development

- **Create a national database on low-carbon materials for cement, concrete, and asphalt**
  - The Federal Highway Administration (FHWA) should collaborate with private companies, trade organizations, academia, State DOTs, and standard-setting bodies to create and maintain a database that captures information on the performance characteristics and emissions reduction achieved by materials as they come to market. This can improve information access to State DOTs, contractors, and engineers on low-carbon materials, accelerating their adoption by improving worker knowledge and confidence. Additionally, a database can inform material lists maintained by standard-setting bodies by providing credible performance data, accelerating the acceptance of low-carbon materials.

- **Establish a network of research, education, and training centers for cement, concrete and asphalt**
  - For asphalt, the National Center for Asphalt Technology has been on the leading edge of asphalt technology and has demonstrated success in transferring knowledge into practice, such as through the adoption of BMD by Tennessee and Alabama. Establishing additional centers around the country to conduct research and provide educational and training opportunities to states and workers can accelerate and increase access to the tools and resources needed to shift to BMD.
  - For cement and concrete, the U.S. Department of Transportation should leverage the University Transportation Centers program to develop training programs and curricula for performance specifications.[69] This program's history of using competitive solicitations to advance specific objectives is well suited to addressing gaps identified in this report, such as designing and testing mixtures under various environmental conditions and contexts.

Streamline Specification Development and Expand Testing Availability

- **Bolster basic research & development in asphalt and concrete mix designs, tests, and testing equipment**
  - Continued federal research and development is necessary to develop and advance innovations in materials, technologies, and testing, as well as provide the foundation for specification development and ultimately commercialization.

- **Establish a network of testing laboratories for cement and concrete**
  - To address testing distrust and availability, a grant program administered by FHWA can establish testing laboratories nationwide. Enhancing access to testing and sharing best

practices would advance trust in testing, a critical component of performance specifications. This can be modeled on the Concrete Testing Adherence Collaboration (CTAC), an effort launched by the Colorado Ready Mixed Concrete Association to create uniform testing in the Colorado concrete industry based on existing standards.

Bolster Technology Validation and Deployment

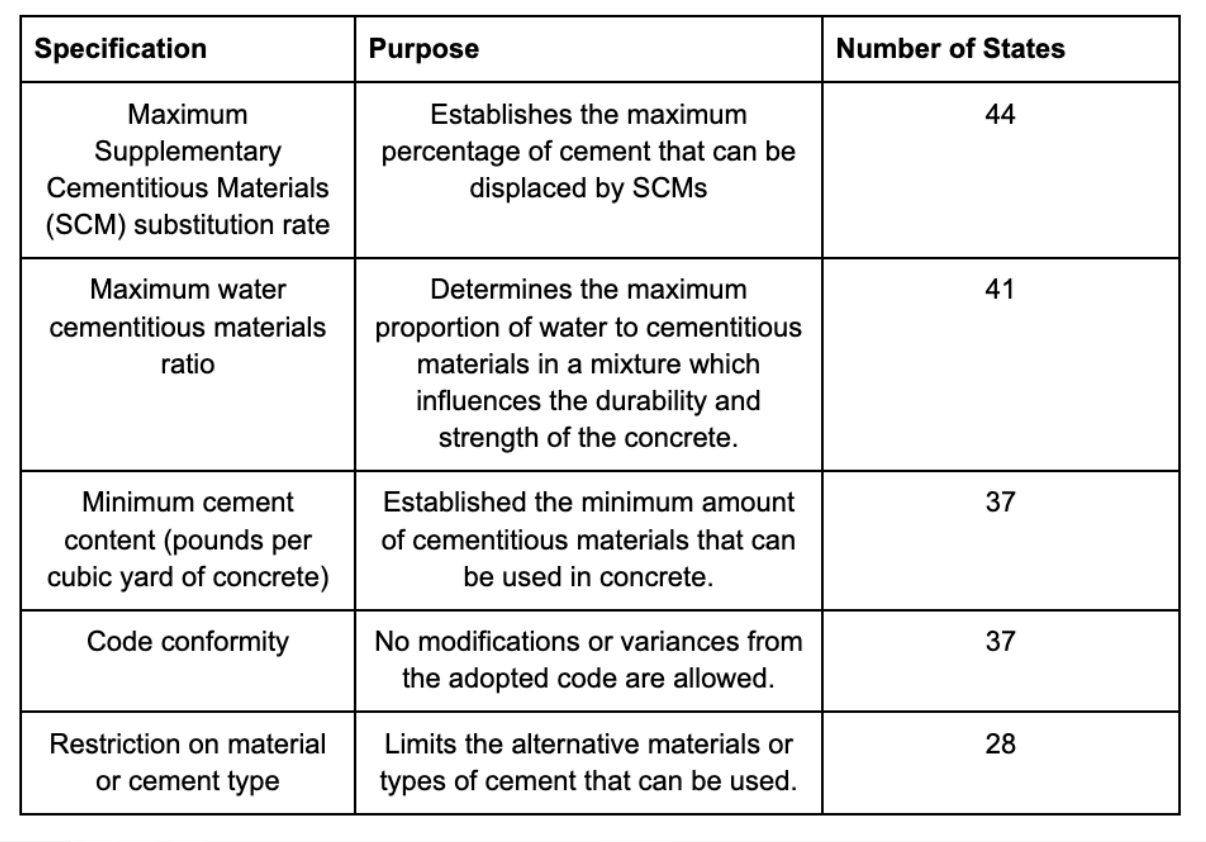
- **Tie grants for federal projects to their use of performance specifications or Balanced Mix Designs**
  - Requiring State DOTs or Highway Authorities to adopt some degree of performance specifications or BMD to access federal grants can accelerate the uptake of these specifications and provide the validation that de-risks broader adoption. In 2018, 92% of total federal expenditure on transportation was through federal grants to state and local governments.[70] This funding would also cover any increased costs from testing equipment and labor involved in first-of-a-kind performance specifications projects and provide demand certainty for innovations.

- **Direct the U.S. DOT to conduct a demonstration project program**
  - Directing the U.S. DOT to fund non-trivial federal construction projects with low risk-to-life safety can demonstrate the feasibility of the materials that have undergone preliminary testing and validation. Priority should be given to project proposals that use low-carbon cement and concrete and use current equipment and production facilities. Offtake agreements are a potentially powerful tool, especially if directly contracted between buyers and producers, because they simplify value chains and provide a strong demand signal for producers to raise financing to invest in emissions reduction.

Appendix A. Synthesis of the State-by-State Specification Landscape for Cement and Concrete

This report examined State DOT specifications or construction manuals in order to document and analyze the prevalence and stringency of regulations governing concrete, cement, and asphalt use in public works. This report first focused on cast-in-place and precast concrete structures and concrete pavements, which represent the largest share of cement and concrete end-uses. Next, the authors identified and collected specification data on materials that are the most commonly used either as traditional materials or as substitutions for or additions to cement in concrete production.

The analysis revealed that at least one type of prescriptive specification exists for cement and concrete materials and end-uses across all U.S. states, highlighting the nationwide regulatory status quo that functions as a barrier to innovation. See Table A1 for the 5 most prevalent specifications and see Figure A1 for a map illustrating their geographic prevalence.



Specification	Purpose	Number of States
Maximum Supplementary Cementitious Materials (SCM) substitution rate	Establishes the maximum percentage of cement that can be displaced by SCMs	44
Maximum water cementitious materials ratio	Determines the maximum proportion of water to cementitious materials in a mixture which influences the durability and strength of the concrete.	41
Minimum cement content (pounds per cubic yard of concrete)	Established the minimum amount of cementitious materials that can be used in concrete.	37
Code conformity	No modifications or variances from the adopted code are allowed.	37
Restriction on material or cement type	Limits the alternative materials or types of cement that can be used.	28

Table A1. The number of states that have at least one of the five most prevalent types of prescriptive specification.

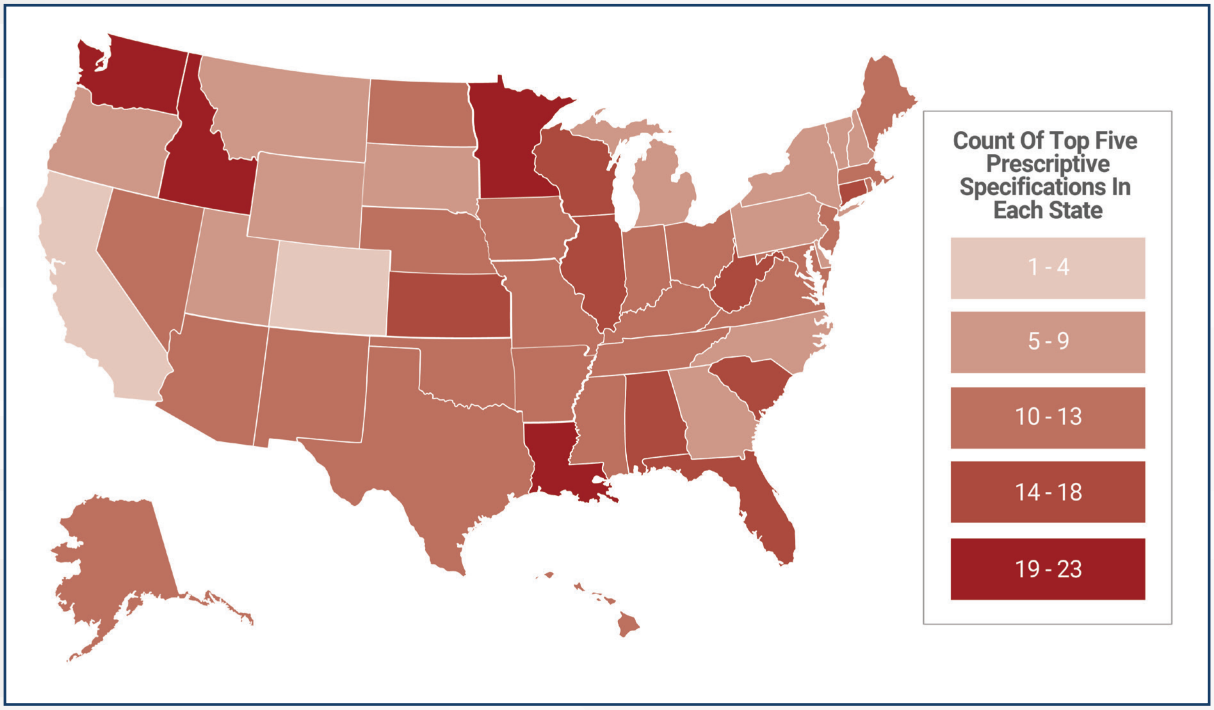


Figure A1. For each state we have counted the total number of the top five prescriptive specifications. These are maximum SCM substitution rate, maximum water cementitious ratio, minimum cement content, code conformity, and restriction on material or cement type.

The most prevalent type of prescriptive specification is maximum cement substitution rates for SCMs. SCMs have been used in concrete mixtures for decades due to their varying ability to improve the performance of concrete as well as reduce costs. The two most commonly used types of SCMs are fly ash and slag. Fly ash is a waste residue from coal combustion[71] and slag, also called blast furnace slag, is a waste material from iron production.[72]

Figure A2 displays the prevalence of maximum cement substitution rates for general SCM replacement and specific substitution rates for fly ash and slag. The data points cover State DOT specifications for concrete pavements and structures, including precast concrete applications. The horizontal axis represents, as percentage substitution rate, the material's quartile range as well as outliers the report identified: the 70-75% range. The vertical axis represents the frequency or count of maximum substitutions across states and end-uses. Some states refer to SCMs that may also include silica fume and raw or calcined natural pozzolans in specifications, while others have separate specifications for different types of SCMs, such as fly ash and slag. This chart therefore reflects the language used by states in their manuals.

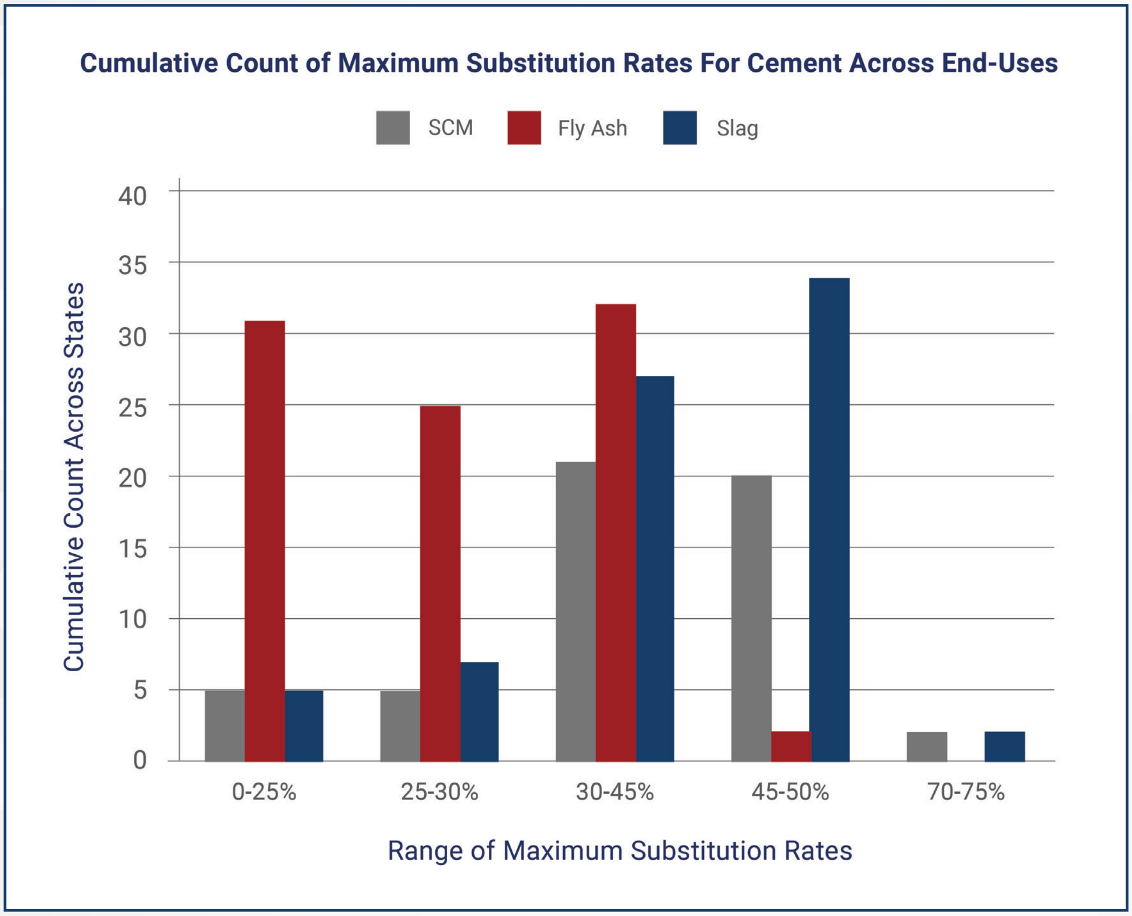


Figure A2. This chart shows the prevalence of prescriptive specifications for maximum substitution rates of SCMs, fly ash and slag in concrete structures, concrete pavements, and precast concrete applications. This analysis shows fly ash and slag are both types of SCMs but are shown separately to reflect that some states refer to SCMs in specifications while others have separate specifications for different SCMs. The range of maximum substitution rates reflects the quartile ranges for the combination of all three materials as well as outliers the report identified. These outliers are in the 70-75% range.

The second most common type of specification is a prescriptive limit on the maximum ratio of water to cementitious materials in a concrete mixture. The relative amount of water in the concrete mixture influences the workability of fresh concrete as well as the durability and strength of hardened concrete. While higher ratios lead to mixtures with greater workability, lower ratios have greater strength. As Figure A3 highlights, one-half of these prescriptive specifications limit ratios to at or below 0.45, which limits concrete producers to design mixtures with higher volumes of cement relative to water. Cement production represents the primary emissions source in concrete, so a higher ratio equates to lower emissions.

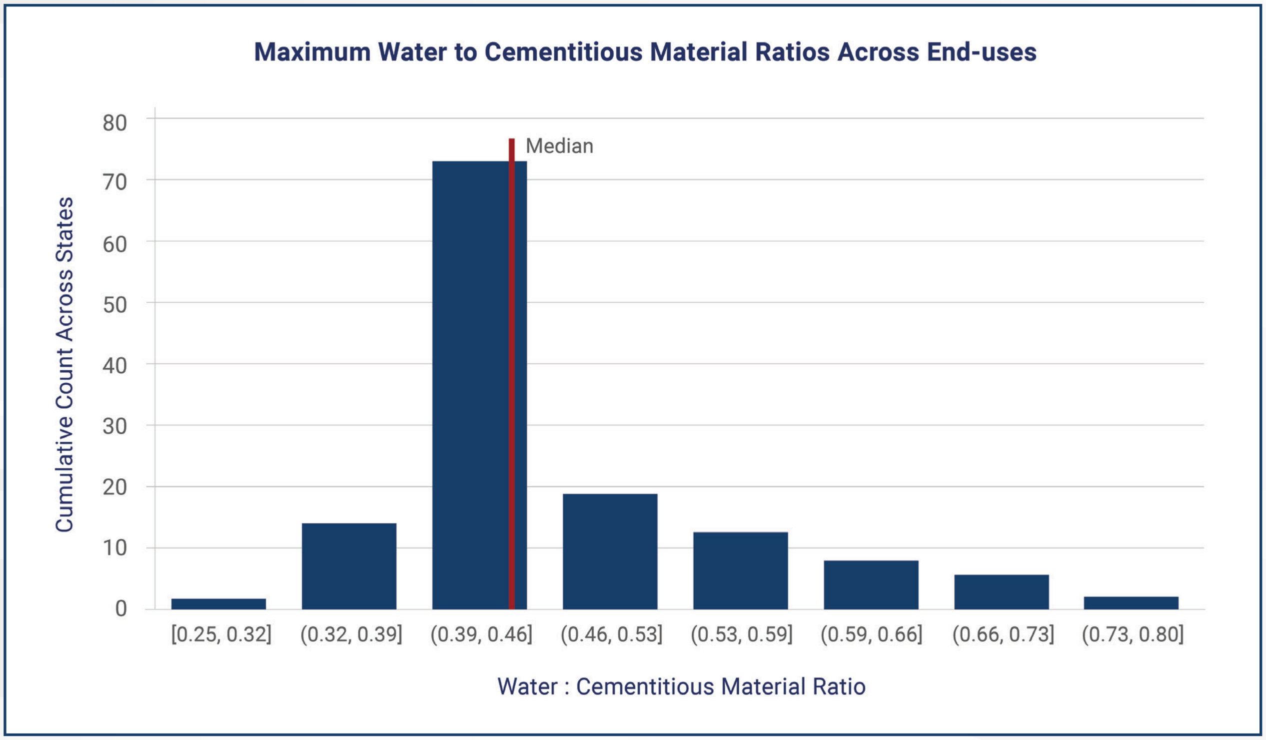


Figure A3. This chart shows the cumulative count across end-uses and states of prescriptive specification for maximum water to cementitious material ratios. The median ratio was 0.45.

The third most prevalent specification type is for the minimum cement content of concrete in pounds per cubic yard (lbs/yd³). The report found that 37 states have at least one prescription on minimum cement content with half of these being at or below 564 lbs/yd³, see Figure A4.

Minimum cement content specifications that are greater than what may be required for the material to perform increase emissions by inhibiting the use of lower carbon materials as substitutes. They also add compliance complexity and cost for concrete producers who have limited flexibility to design mixtures using available materials.

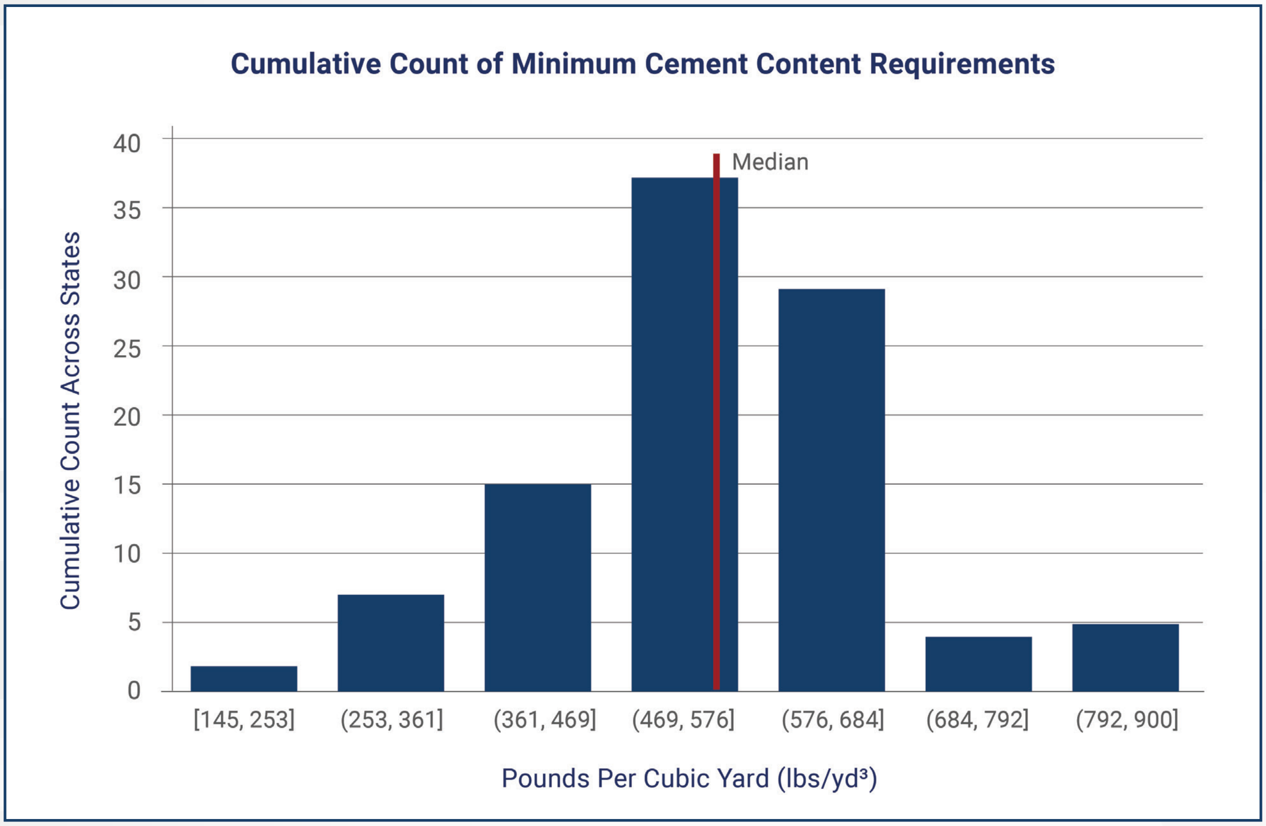
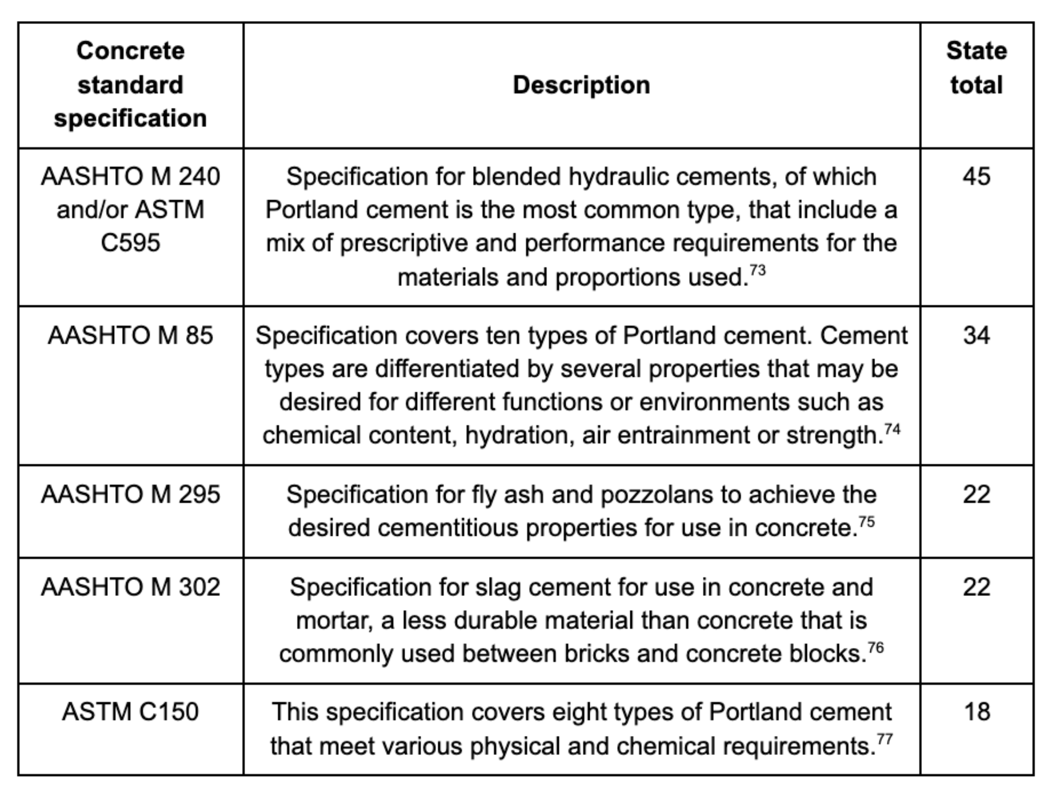


Figure A4. This chart shows the cumulative count of end-uses across all states with prescriptive specifications for minimum cement content in pounds per cubic yard (lbs/yd³). The median was 564 lbs/yd³.

Standard specifications created by organizations such as ASTM International and the American Association of State Highway and Transportation Officials (AASHTO) are often the starting point for many State DOTs, and this report's analysis reveals that standard specifications are commonly used without modifications. Table A2 below shows the standard specifications that were referenced by a State DOT and the number of states that referred to the standard specification at least once within their manual.

A key finding is that the majority of State DOTs default to standard specifications as they are written, with the most common examples adopted by states shown in Table A2 - see Figure A5 for a map illustrating their geographic prevalence. Updating existing standard specifications or introducing new standard performance specifications will provide states and end-users with the confidence to adopt new practices and utilize alternative or innovative materials.



Concrete standard specification	Description	State total
AASHTO M 240 and/or ASTM C595	Specification for blended hydraulic cements, of which Portland cement is the most common type, that include a mix of prescriptive and performance requirements for the materials and proportions used.[73]	45
AASHTO M 85	Specification covers ten types of Portland cement. Cement types are differentiated by several properties that may be desired for different functions or environments such as chemical content, hydration, air entrainment or strength.[74]	34
AASHTO M 295	Specification for fly ash and pozzolans to achieve the desired cementitious properties for use in concrete.[75]	22
AASHTO M 302	Specification for slag cement for use in concrete and mortar, a less durable material than concrete that is commonly used between bricks and concrete blocks.[76]	22
ASTM C150	This specification covers eight types of Portland cement that meet various physical and chemical requirements.[77]	18

Table A2. Number of states that refer to at least one concrete code standard specification

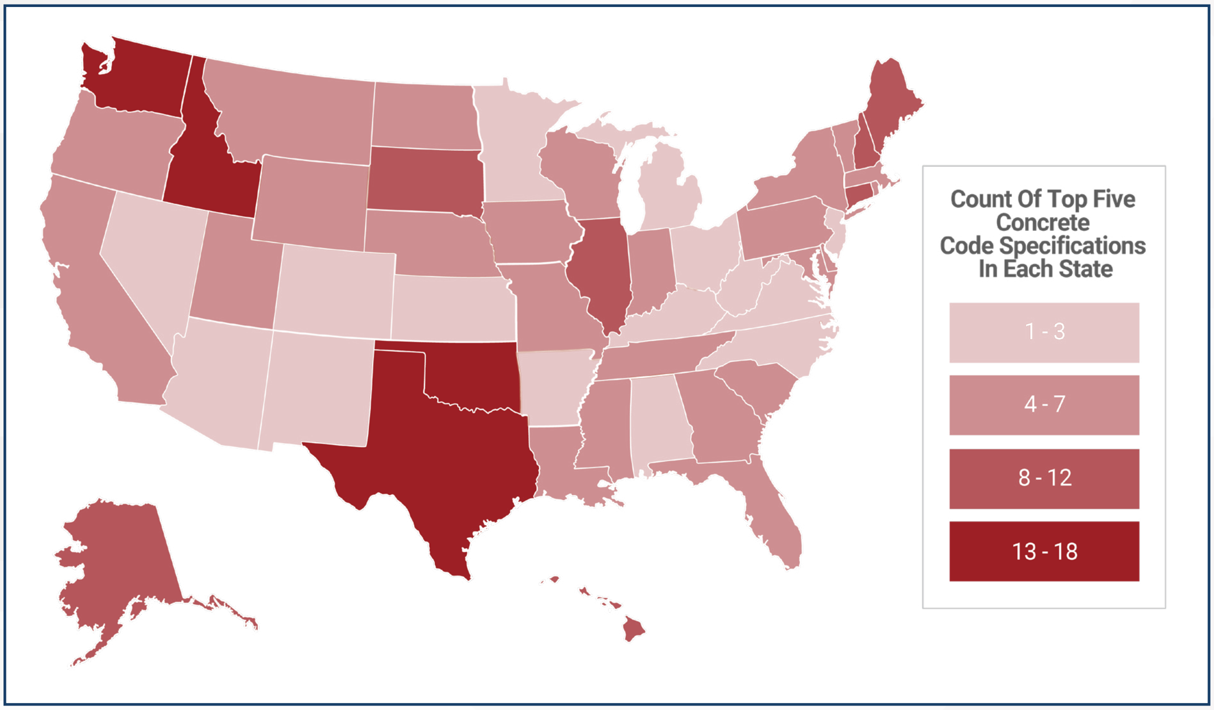
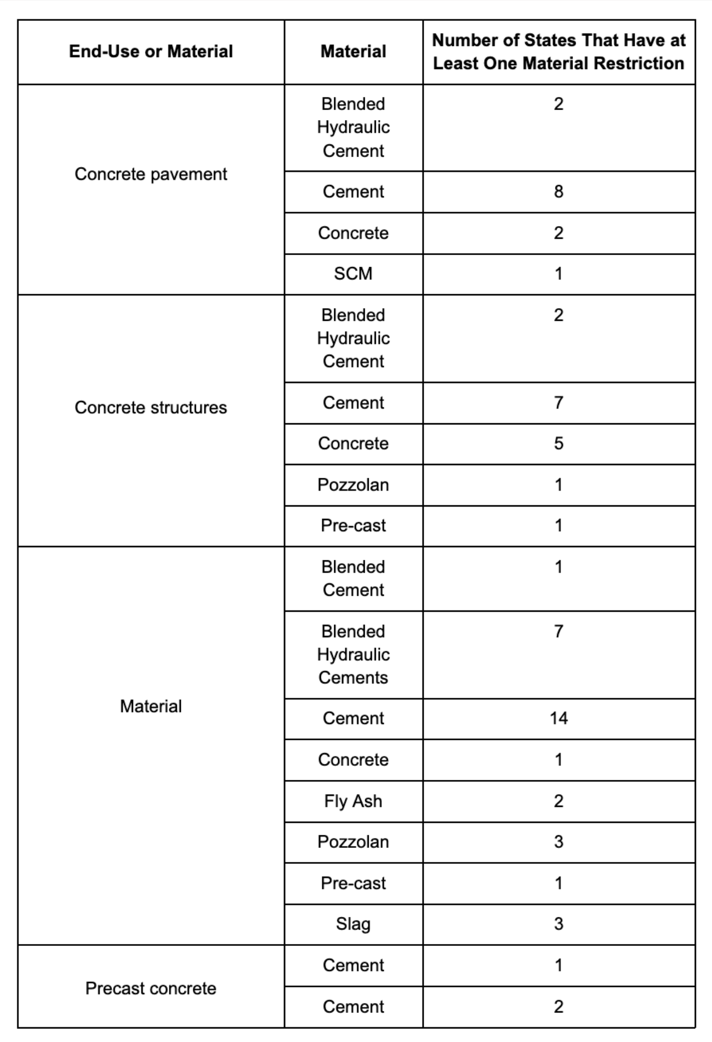


Figure A5. For each state we have counted the total number of the top five concrete code specifications. These codes are AASHTO M 240 and/or ASTM C595, AASHTO M 85, AASHTO M 295, AASHTO M 302, and ASTM C150.

Within the report's research scope, it found 34 states referenced AASHTO M 85, a specification that provides requirements for the ten types of Portland cement. In contrast, only 2 states referenced ASTM C 1157, a performance standard specification that places no restrictions on the materials or proportions used for making concrete.[78] A survey conducted by the National Concrete Consortium in the spring of 2022 had a broader scope than this report but reached similar conclusions: there is limited adoption of performance specifications such as ASTM C1157 at State DOTs. Their survey of 36 State DOT officials found that, for all concrete end-uses, only 9 out of 36 states (25%) have concrete specifications that allow for the use of ASTM C1157 cement.[79]

States have historically adopted restrictions on the use of materials or types of cement to prescribe the method or materials that achieve a desired engineering performance rather than having performance specifications that provide flexibility in procuring materials or cement that can achieve the desired engineering performance. The report's research revealed that there are thirty cases of a state disallowing or limiting the type of cement that can be used, as displayed in Table A3.



End-Use or Material	Material	Number of States That Have at Least One Material Restriction
Concrete pavement	Blended Hydraulic Cement	2
	Cement	8
	Concrete	2
	SCM	1
Concrete structures	Blended Hydraulic Cement	2
	Cement	7
	Concrete	5
	Pozzolan	1
	Pre-cast	1
Material	Blended Cement	1
	Blended Hydraulic Cements	7
	Cement	14
	Concrete	1
	Fly Ash	2
	Pozzolan	3
	Pre-cast	1
	Slag	3
Precast concrete	Cement	1
	Cement	2

Table A3. Prevalence of restrictions on the types of supplementary cementitious materials or the types of cement that can be used in construction.

Appendix B. Synthesis of the State-By-State Specification Landscape for Asphalt

Key takeaways:

- BMD adoption is limited but growing - only one state has adopted fully performance specifications (Approach D) for at least one application.
- Substitution limits on RAP and/or RAS are the key prescriptive specifications - 36 states have some maximum substitution limit.
- RAS substitution limits are stricter than RAP limits.
- Tennesse is the only state that has adopted BMD Approach D.

Forty-nine out of fifty U.S. states still have conventional volumetric requirements for asphalt pavement applications. However, the adoption of BMD has been increasing, with different states choosing to adopt variations of approaches A through D highlighted above. As of the second quarter of 2023, 17 states are in the pre-implementation phase to adopt BMD, which includes building technical capacity and training agencies at the state level, benchmarking mixtures, acquiring performance testing equipment and selecting the appropriate tests for specific applications.

Six states have adopted Approach A for Balanced Mix Design (BMD) for at least one application. These states are Illinois, Louisiana, New Jersey, Texas, Wisconsin, and Vermont. Additionally, Virginia uses both Approach A and Approach D, while New Jersey uses both Approach A and B. In total, eight states use Approach A BMD either solely or in combination with another approach.Two states - Oklahoma and Missouri - have adopted Approach B solely while for Approach C Alabama and California have soley adopted this approach.

Tennessee is noteworthy because it is the only state that has fully embraced BMD Approach D - removing volumetric requirements for all applications, with a draft specification released in 2020.[80] The state-by-state landscape is summarized in Figure B1.

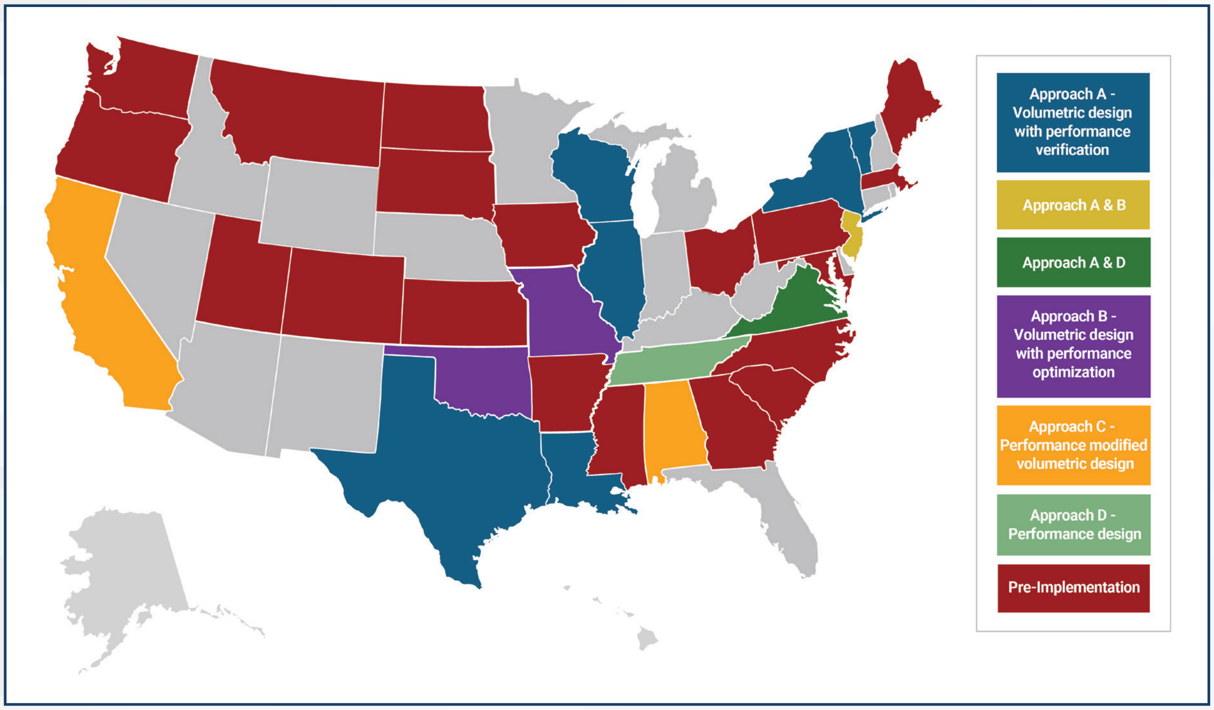


Figure B1: State-by-state implementation of BMD as of Q3 2023 [updated quarterly by National Center for Asphalt Technology (NCAT)]. Credit: National Asphalt Pavement Association

Given that RAP and RAS substitution for virgin asphalt is the most important driver for reducing costs and emissions, the report focused on State DOT specifications that limit RAP and RAS substitution. Substitution limits for RAP and combined RAP/RAS were analyzed based on allowable limits as a percentage of virgin asphalt binder replacement. RAS substitution limits were analyzed based on allowable limits as a percentage of the mass of the asphalt mixture.

This report collected specification data from State DOT construction manuals for RAP, RAS, and the combined use of RAP and RAS. The report's analysis found that over half of the country has limitations on the amount of RAP and/or RAS that may be used in asphalt, see Table B1. When used in combination, 11 states impose limits on the percentage of asphalt that may be substituted.

	Recycled Asphalt Pavement (RAP)	Recycled Asphalt Shingles (RAS)	Combination of RAP & RAS
Maximum Substitution Limit	31	16	11
Prohibition	3	5	3
No Explicit Maximum	4	1	3

Table B1. Count of states with each prescription for asphalt pavement.

For RAP specifically, there are 3 states that prohibit its use in at least one asphalt use case. A histogram of maximum substitution limits on RAP is shown in Figure B2 below: the report found that half of states have maximum substitution rates for RAP at or below 30% of the asphalt.

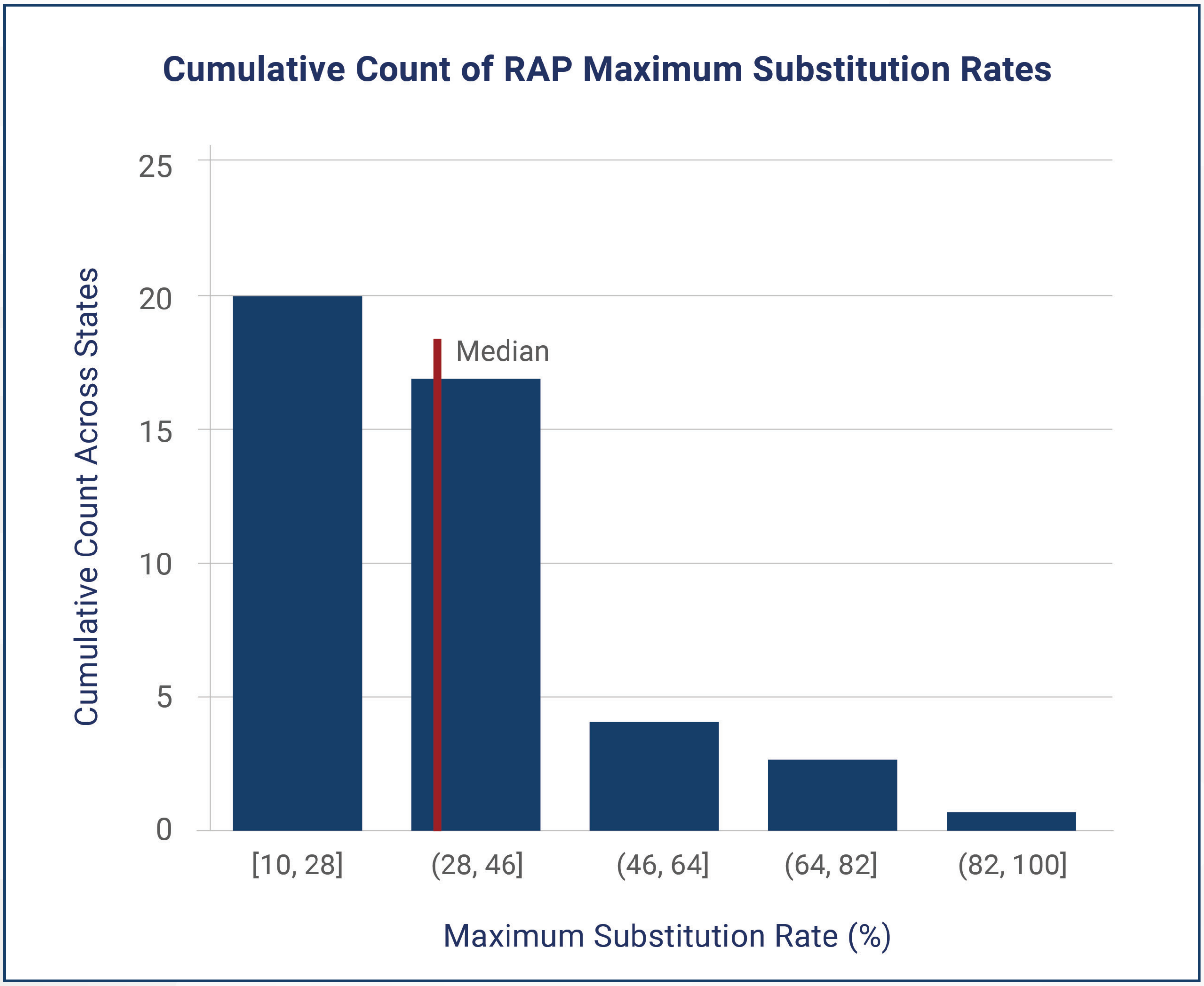


Figure B2. This chart shows the cumulative count across states of maximum substitution rates for RAP in asphalt pavement as a percentage of virgin asphalt binder replacement. The median was 30%.

For RAS specifically, there are 5 states that prohibit its use in at least one asphalt use case. Figure B3, below, shows that over half of maximum substitution rates for RAS are at or below 5% of the asphalt pavement.

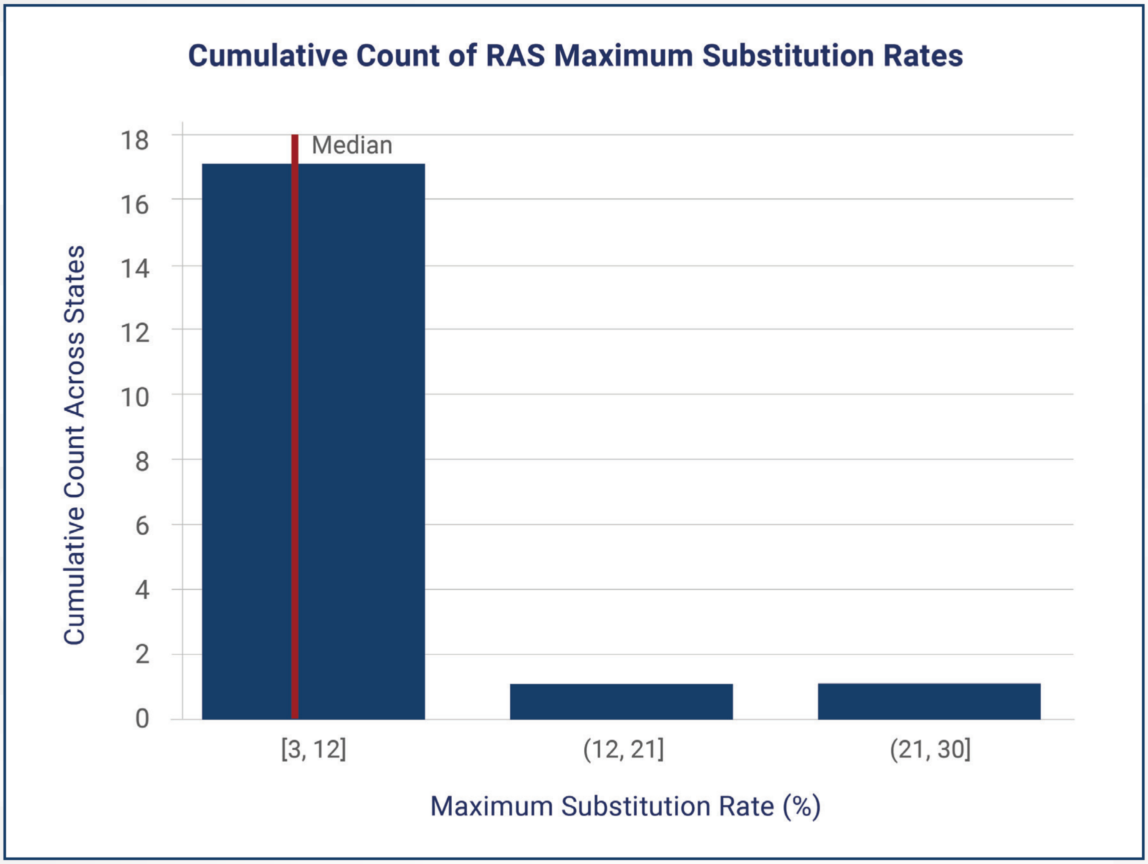


Figure B3. This chart shows the cumulative count across states for maximum substitution rates for RAS in asphalt pavement as a percentage of the mass of the asphalt mixture. The RAS maximum substitution rate for Maryland was excluded because it was expressed as a percentage of binder replacement, not the mass of the asphalt mixture. The median value was 5%.

The use of RAP and RAS in combination is prohibited in 3 states for at least one asphalt end use. Figure B4 below displays substitution limits on the combination of RAP and RAS. The report's research found that half of maximum substitution rates are at or below 27% for the combined use of RAP and RAS.

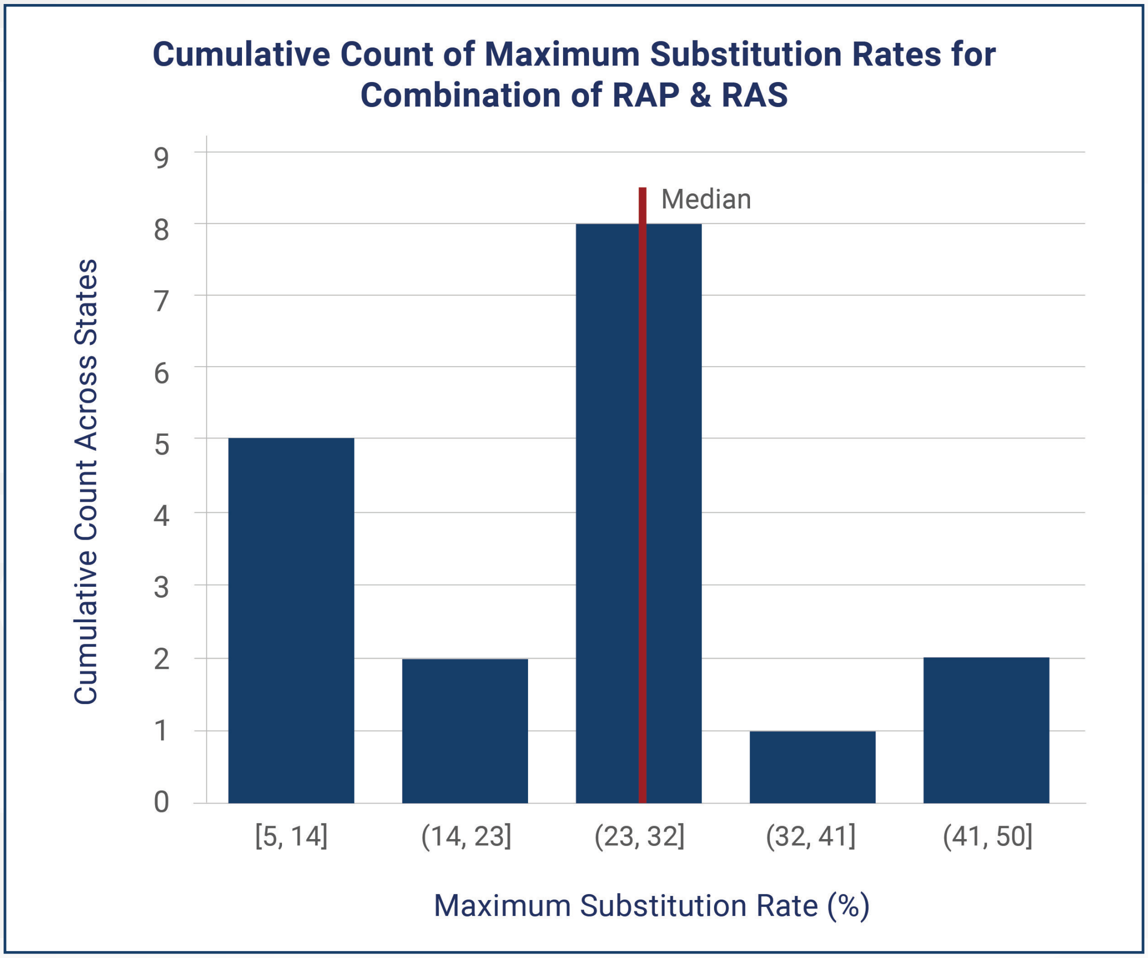


Figure B4. This chart shows the cumulative count across states for maximum substitution rates for the combination of RAP & RAS in asphalt pavement as a percentage of virgin asphalt binder replacement. The median value was 27%.

Bibliography

1. *Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. (2022). Global Cement and Concrete Association. https://gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete-Future-Roadmap-Document-AW-2022.pdf*
2. *Ibid.*
3. *Pathways to Commercial Liftoff: Low-Carbon Cement. (2023). Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf*
4. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. (2023). Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021*
5. *Performance-Engineered Concrete Paving Mixtures final report. (2022). National Concrete Pavement Technology Center Iowa State University. https://intrans.iastate.edu/app/uploads/2023/04/performance-engineered_concrete_paving_mixtures_w_cvr.pdf*
6. *Shacat, J., Willis, J. R., & Ciavola, B. (2022). GHG Emissions Inventory For Asphalt Mix Production in the U.S.: Current Industry Practices and Opportunities to Reduce Futur Emissions (SIP 106). National Asphalt Pavement Association. https://www.asphaltpavement.org/uploads/documents/Sustainability/SIP-106_GHG_Emissions_Inventory_for_Asphalt_Mix_Production_in_the_US_%E2%80%93_NAPA_June_2022.pdf*
7. *Greenhouse Gas Emissions from a Typical Passenger Vehicle. (2016, January 12). [Overviews and Factsheets]. U.S. Environmental Protection Agency. https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle*
8. *Lovins, A. (2021). Profitably Decarbonizing Heavy Transport and Industrial Heat: Transforming These “Harder-to-Abate” Sectors Is Not Uniquely Hard and Can Be Lucrative. Rocky Mountain Institute. https://rmi.org/wp-content/uploads/2021/07/rmi_profitable_decarb.pdf*
9. *GSA Lightens the Environmental Footprint of its Building Materials. (2022, March 30). U.S. General Services Administration. https://www.gsa.gov/about-us/newsroom/news-releases/gsa-lightens-the-environmental-footprint-of-its-building-materials-03302022*
10. *Hasanbeigi, A., & Harshvardhan, K. (2021). Scale of Government Procurement of Carbon-Intensive Materials in the U.S. Global Efficiency Intelligence. https://www.globalefficiencyintel.com/scale-of-government-procurement-of-carbonintensive-materials-in-us*
11. *Talati, S., Merchant, N., & Neidl, C. (2020). Paving the Way for Low-Carbon Concrete: Recommendations for a Federal Procurement Strategy. Carbon 180. https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/5fd95907de113c3cc0f144af/1608079634052/Paving+the+Way+-for+Low-Carbon+Concrete*
12. *Griffiths, S., Sovacool, B. K., Furszyfer Del Rio, D. D., Foley, A. M., Bazilian, M. D., Kim, J., & Uratani, J. M. (2023). Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options. Renewable and Sustainable Energy Reviews, 180, 113291. https://doi.org/10.1016/j.rser.2023.113291*
13. *Pathways to Commercial Liftoff: Low-Carbon Cement. (2023). Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf*
14. *Shacat, J., Willis, J. R., & Ciavola, B. (2022). GHG Emissions Inventory For Asphalt Mix Production in the U.S.: Current Industry Practices and Opportunities to Reduce Futur Emissions (SIP 106). National Asphalt Pavement Association. https://www.asphaltpavement.org/uploads/documents/Sustainability/SIP-106_GHG_Emissions_Inventory_for_Asphalt_Mix_Production_in_the_US_%E2%80%93_NAPA_June_2022.pdf*
15. *Technology Roadmap—Low-Carbon Transition in the Cement Industry. (2018). International Energy Agency. https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf*
16. *Woodall, C. (2021). Report on Decarbonization in Concrete and Pavements. ClearPath. https://static.clearpath.org/2022/03/cement-report-feb-2021-22.pdf*
17. *Technology Roadmap—Low-Carbon Transition in the Cement Industry. (2018). International Energy Agency. https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf*
18. *Ibid.*
19. *Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf*
20. *2021 International Building Code: Chapter 19 Concrete. (2020). ICC Digital Codes. https://codes.iccsafe.org/content/IBC2021P1/chapter-19-concrete*
21. *Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf*
22. *Ibid.*
23. *Ibid.*
24. *Ibid.*
25. *How are ASTM standards developed? (n.d.). American Society for Testing and Materials. Retrieved October 31, 2023, from https://www.astm.org/get-involved/consumer-participation/what-to-expect.html*
26. *American Association of State Highway & Transportation Officials (AASHTO). User Guide for the Portland & Blended Cement Technical Committee. Retrieved from https://transportation.org/product-evaluation-and-audit-solutions/wp-content/uploads/sites/49/2023/03/PBC-User-Guide1.pdf*

27. American Association of State Highway & Transportation Officials (AASHTO). About. https://transportation.org/about/#:~:text=AASHTO's%20policy%20development%2C%20standards%2Dsetting,year%20and%20typically%20meet%20annually.
28. Airport Pavement Design & Construction. (2023). Federal Aviation Administration. https://www.faa.gov/airports/engineering/pavement_design
29. National Center for Asphalt Technology at Auburn University. (n.d.). National Center for Asphalt Technology at Auburn University. Retrieved October 31, 2023, from https://eng.auburn.edu/research/centers/ncat/
30. Prescription to Performance (P2P) Initiative. (n.d.). National Ready Mixed Concrete Association. Retrieved October 31, 2023, from https://www.nrmca.org/association-resources/research-and-engineering/p2p/
31. Ibid.
32. Obla, K., & Lobo, C. (2006). Experimental Case Study Demonstrating Advantages of Performance Specifications. RMC Research Foundation. https://www.nrmca.org/wp-content/uploads/2020/06/P2P_Lab_reportjan2006.pdf
33. Hajj, E., Aschenbrener, T., & Nener-Plante, D. (2022). Positive Practices, Lessons Learned, and Challenges When Implementing Balanced Design of Asphalt Mixtures: Site Visits. University of Nevada, Reno. https://scholarworks.unr.edu/bitstream/handle/11714/8127/WRSC-TR-22-11_BMD_Case_Studies_Summary_Report_acc.pdf?sequence=1&isAllowed=y
34. Obla, K., Lobo, C., Hong, R., & Kim, H. (2015). Optimizing Concrete Mixtures for Performance and Sustainability. RMC Research Foundation. https://cdnassets.hw.net/3a/7e/16b245b543608692298935c932ee/optimizingconcretemixturesfinalreport.pdf
35. Casillas, B., Almutairi, W., Lebow, C., & Hale, M. (2020). Examining the Required Cement Content. Department of Civil Engineering University of Arkansas in Fayetteville. https://www.ardot.gov/wp-content/uploads/2021/02/TRC1602.pdf
36. Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf
37. Lobo, C., & Obla, K. (2016, March 16). Performance-Based Specifications: State of the Industry and Way Forward. https://seain.org/images/meeting/030316/2016_Spring_Conference_Presenstations/session_2___performance_based_specifications_state_of_the_industry_and_way_forward.pdf
38. Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf
39. Mineral Commodity Summaries 2022—Iron and Steel Slag. (2022). United States Geological Survey. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-steel-slag.pdf
40. Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf
41. Mineral Commodities Summaries: Cement. (2023). U.S. Geological Survey. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf
42. Material efficiency in clean energy transitions. (2019). International Energy Agency. https://doi.org/10.1787/aeaaccd8-en
43. Hajj, E., Aschenbrener, T., & Nener-Plante, D. (2022). Positive Practices, Lessons Learned, and Challenges When Implementing Balanced Design of Asphalt Mixtures: Site Visits. University of Nevada, Reno. https://scholarworks.unr.edu/bitstream/handle/11714/8127/WRSC-TR-22-11_BMD_Case_Studies_Summary_Report_acc.pdf?sequence=1&isAllowed=y
44. Pathways to Commercial Liftoff: Low-Carbon Cement. (2023). Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf
45. Hajj, E., Aschenbrener, T., & Nener-Plante, D. (2022). Positive Practices, Lessons Learned, and Challenges When Implementing Balanced Design of Asphalt Mixtures: Site Visits. University of Nevada, Reno. https://scholarworks.unr.edu/bitstream/handle/11714/8127/WRSC-TR-22-11_BMD_Case_Studies_Summary_Report_acc.pdf?sequence=1&isAllowed=y
46. Hajj, E., Aschenbrener, T., & Nener-Plante, D. (2022). Positive Practices, Lessons Learned, and Challenges When Implementing Balanced Design of Asphalt Mixtures: Site Visits. University of Nevada, Reno. https://scholarworks.unr.edu/bitstream/handle/11714/8127/WRSC-TR-22-11_BMD_Case_Studies_Summary_Report_acc.pdf?sequence=1&isAllowed=y
47. Material efficiency in clean energy transitions. (2019). International Energy Agency. https://doi.org/10.1787/aeaaccd8-en
48. Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf
49. Shacat, J., Willis, J. R., & Ciavola, B. (2022). GHG Emissions Inventory For Asphalt Mix Production in the U.S.: Current Industry Practices and Opportunities to Reduce Futur Emissions (SIP 106). National Asphalt Pavement Association. https://www.asphaltpavement.org/uploads/documents/Sustainability/SIP-106_GHG_Emissions_Inventory_for_Asphalt_Mix_Production_in_the_US_%E2%80%93_NAPA_June_2022.pdf
50. Greenhouse Gas Emissions from a Typical Passenger Vehicle. (2016, January 12). [Overviews and Factsheets]. U.S. Environmental Protection Agency. https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle
51. Lovins, A. (2021). Profitably Decarbonizing Heavy Transport and Industrial Heat: Transforming These “Harder-to-Abate” Sectors Is Not Uniquely Hard and Can Be Lucrative. Rocky Mountain Institute. https://rmi.org/wp-content/uploads/2021/07/rmi_profitable_decarb.pdf
52. Chen, Z., & Lalit, R. (2023). The 3Cs of Innovation in Low-Carbon Concrete: Clinker, Cement, and Concrete. Rocky Mountain Institute. https://rmi.org/insight/innovation-in-low-carbon-concrete/
53. Ultra-Low Carbon Concrete for Industrial Decarbonization. (n.d.). Carbonbuilt. Retrieved October 31, 2023, from https://carbonbuilt.com/
54. Sublime Systems. (n.d.). Sublime Systems. Retrieved October 31, 2023, from https://sublime-systems.com/technology/

55. *Asphalt Pavement Industry Goals for Climate Stewardship: Toward Net Zero Carbon Emissions—National Asphalt Pavement Association. (n.d.). National Asphalt Pavement Association. Retrieved November 6, 2023, from https://www.asphaltpavement.org/climate/industry-goals*
56. *Waidelich, W. (2014). Recycled Materials in Asphalt Pavements. https://www.fhwa.dot.gov/pavement/recycling/141020.pdf*
57. *Standard Specifications for Construction Volume I - Division I and III. (n.d.). Minnesota Department of Transportation. Retrieved October 23, 2023, from https://www.dot.state.mn.us/pre-letting/spec/*
58. *Balanced Mix Design (BMD) Case Studies Virtual Workshop: Moving Forward with Implementation. (2021). Federal Highway Administration Resource Center. https://www.fhwa.dot.gov/pavement/asphalt/pubs/20210722_bmd_workshop_flyer_508c_finalv3.pdf*
59. *Standard Specification for Cements that Require Carbonation Curing. (n.d.). [ASTM International]. Retrieved November 6, 2023, from https://www.astm.org/c1905_c1905m-23.html*
60. *Ibid.*
61. *Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf*
62. *West, R., Rodezno, C., Leiva, F., & Yin, F. (2018). Development of a Framework for Balanced Mix Design (NCHRP 20-07/Task 406). National Center for Asphalt Technology at Auburn University. https://www.eng.auburn.edu/research/centers/ncat/files/technical-reports/rep21-03.pdf*
63. *Taylor, P., Yurdakul, E., Wang, X., & Wang, X. (2015). Concrete Pavement Mixture Design and Analysis (MDA): An Innovative Approach to Proportioning Concrete Mixtures [Technical Report]. National Concrete Pavement Technology Center Iowa State University. https://wisconsindot.gov/Documents/doing-bus/eng-consultants/cnslt-rsrces/tools/qmp/performance-based-PCC-mix-design-1-11-2017.pdf*
64. *Equipment Loan Program—Mobile Asphalt Technology Center. (n.d.). Federal Highway Administration. Retrieved November 9, 2023, from https://www.fhwa.dot.gov/pavement/asphalt/MATC/equipment-loan-program.cfm*
65. *Van Dam, T., Sutter, L., Hooton, D., Lopez, S., & Innis, A. (2023). Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete. Breakthrough Energy Foundation. https://mnconcretecouncil.com/application/files/2916/8937/1438/Sutter_Low_Embodied_Carbon_Materials_July_2023.pdf*
66. *Taylor, A., Moore, J., & Moore, N. (2022). NCAT Performance Testing Round Robin (NCAT REPORT 22-01). National Center for Asphalt Technology. https://eng.auburn.edu/research/centers/ncat/files/technical-reports/rep22-01.pdf*
67. *Pathways to Commercial Liftoff: Low-Carbon Cement. (2023). Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf*
68. *Pathways to Commercial Liftoff: Low-Carbon Cement. (2023). Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf*
69. *University Transportation Centers. (n.d.). Department of Transportation. Retrieved November 6, 2023, from https://www.transportation.gov/content/university-transportation-centers*
70. *Hasanbeigi, A., & Harshvardhan, K. (2021). Scale of Government Procurement of Carbon-Intensive Materials in the U.S. Global Efficiency Intelligence. https://www.globalefficiencyintel.com/scale-of-government-procurement-of-carbonintensive-materials-in-us*
71. *Fly Ash Facts for Highway Engineers. (2017). Federal Highway Administration. https://www.fhwa.dot.gov/pavement/recycling/fach01.cfm#:~:text=What%20is%20fly%20ash%3F,combustion%20chamber%20by%20exhaust%20gases.*
72. *User Guidelines for Waste and Byproduct Materials in Pavement Construction. (2016). Federal Highway Administration Research and Technology. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/97148/008.cfm*
73. *AASHTO - M 240M/M 240—Standard Specification for Blended Hydraulic Cement. (2021). Global Spec. https://standards.globalspec.com/std/14459527/m-240m-m-240*
74. *AASHTO M 85—Standard Specification for Portland Cement. (2020). Global Spec. https://standards.globalspec.com/std/14214292/AASHTO%20M%2085*
75. *AASHTO M 295—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete | GlobalSpec. (2019). Global Spec. https://standards.globalspec.com/std/13344845/AASHTO%20M%20295*
76. *AASHTO M 302—Standard Specification for Slag Cement for Use in Concrete and Mortars. (2019). Global Spec. https://standards.globalspec.com/std/13344846/AASHTO%20M%20302*
77. *Standard Specification for Portland Cement. (2012). ASTM International. https://www.astm.org/c0150-07.html*
78. *Standard Performance Specification for Hydraulic Cement. (2010). ASTM International. https://www.astm.org/c1157-08a.html*
79. *NCC Spring 2022 State Reports on Sustainability and Concrete Materials. (2022). National Concrete Consortium. https://intrans.iastate.edu/app/uploads/sites/7/2022/05/Sp22-State-Reports_All_220503-1.pdf*
80. *BMD Resource Guide: Tennessee. (2023). National Asphalt Pavement Association. https://www.asphaltpavement.org/uploads/documents/ERT%20Related/BMD_Resource_Guide/TN_-_SOP_05.2023.pdf*