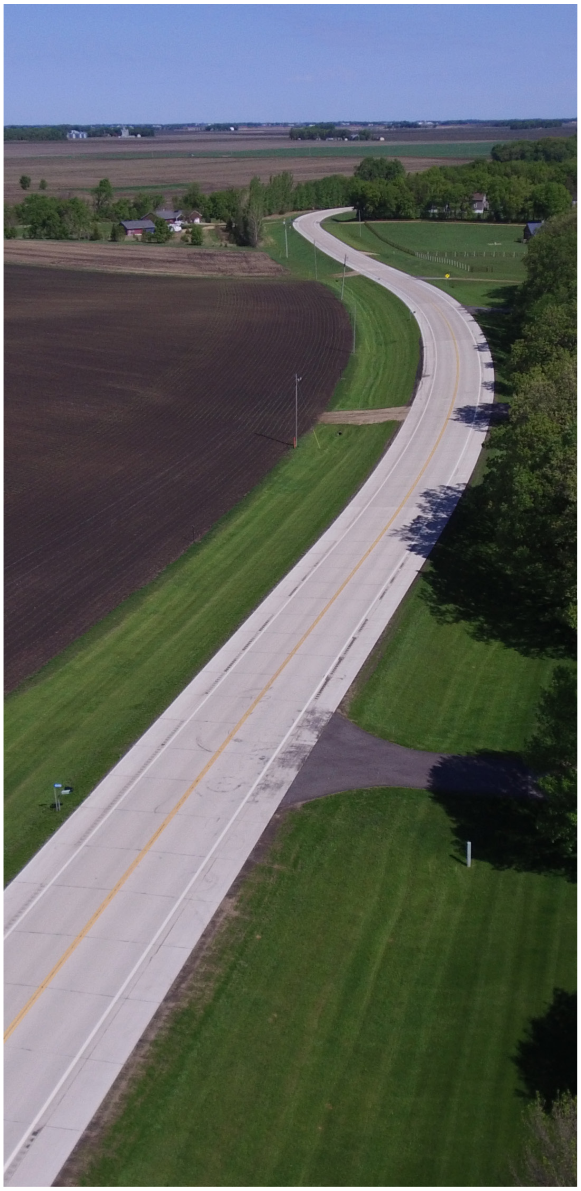
Concrete Pavement's Role in a Sustainable, Resilient Future

Version 1.1

AMERICAN CONCRETE PAVEMENT ASSOCIATION



Overview

Across the globe, millions of miles of pavements are placed or rehabilitated every year. As the worldwide challenge to address climate change persists, decision-makers are called on to make pavement type and treatment selections that must meet ever increasing levels for improving sustainability. Additionally, these selections must be resilient to withstand increasing threats of natural and man-made disasters. This report provides an overview of the research supporting concrete pavement's role in meeting the standards of sustainability and resilience, ultimately creating a future that meets the needs of generations to come.

ACPA

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Section One: Introduction to Sustainability and Resilience

Since ancient times, concrete has been a vital material for the built environment. Many of the earliest concrete civil engineering works remain today as a testament to the material's long lifespan, durability, and resilience. In the modern world, new construction and modernization continue to rely on concrete, which is second only to water as the most consumed material on the planet. Structures built with concrete are designed to last, which is a key objective of sustainable, resilient construction.

The American Concrete Pavement Association (ACPA) is committed to delivering sustainable and resilient concrete pavements to improve America's roadway infrastructure. Work is being done throughout the concrete industry to help reduce the impacts of building and maintaining concrete infrastructure. This report serves as an overview for improving the sustainability of roadways, highways, and airfields with concrete pavements.

What is Sustainability?

As we consider the sustainable benefits of concrete pavements, it is important to begin by defining sustainability. The most accepted definition of sustainability was established in 1983 when the United Nations established the Brundtland Commission to unite countries in pursuit of sustainable development. The group was tasked with identifying a definition of sustainability, and the result of their efforts is a definition that has united global citizens for decades: ***meeting our own needs without compromising the ability of future generations to meet needs of their own.*** A similar definition, more related to infrastructure, defines sustainability as the capacity to maintain a process or state of being into perpetuity, without exhausting the resources upon which it depends nor degrading the environment in which it operates.

In recent years, it has been suggested that for human activity to meet present needs without compromising the prospects of future generations, we need to carefully balance economic, environmental, and societal demands. This concept is often referred to as the "three pillars of sustainability" or the "triple-bottom-line," which illustrates that sustainable solutions are those that incorporate all elements of the triple bottom line.

Concrete pavements, both full-depth and overlays, are a vitally important solution to building a sustainable future—one where roads, highways, airports, and other structures can stand the test of time without frequent repair or replacement.

The Resilience Relationship

Any discussion of a material's sustainability must also include mention of its resilience. Sustainability and resilience work in tandem, with resilience forming the foundation for all three pillars of sustainability. While sustainability deals with known events that can be quantified, resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly after a disruptive event. Unlike sustainability, resiliency deals with unknown events that have high negative impacts like loss due to flood, earthquake, etc. In a changing climate where extreme weather events are greater in frequency and intensity than in the past, it is impossible to have sustainable infrastructure without resilience. A truly sustainable system must incorporate resilience to ensure that these disruptive events will have as little impact as possible and will not significantly increase the need for additional future rehabilitation and reconstruction activities.

The new World Bank and Global Facility for Disaster Reduction and Recovery estimates that every $1 invested in more resilient infrastructure results in $4 of long-term benefit over the infrastructure's expected life. Resilient systems limit the impacts of adverse events such as tropical storms, floods, hurricanes, wildfires, derechos, and droughts. As a result of the increased intensity and frequency of such disruptive events, it is essential for pavements to withstand their impacts, as well as increased loads, from rescue and recovery vehicles that are not accounted for during initial design. As such, decision-makers and specifiers are called on to design pavements that will not fail prematurely or in the wake of disastrous events. With well-defined properties of strength and durability, concrete offers the most resilient pavement material choice.

Sustainable, resilient infrastructure is essential to meeting the demands of the future. Because of its unique strength, durability, and load distributing properties, concrete can improve pavement resilience and the sustainability of the infrastructure in our cities and communities. The challenge presented to global and local communities is how to build more durable structures using concrete, while minimizing the carbon emissions generated during the manufacturing and supplying of cement and concrete.

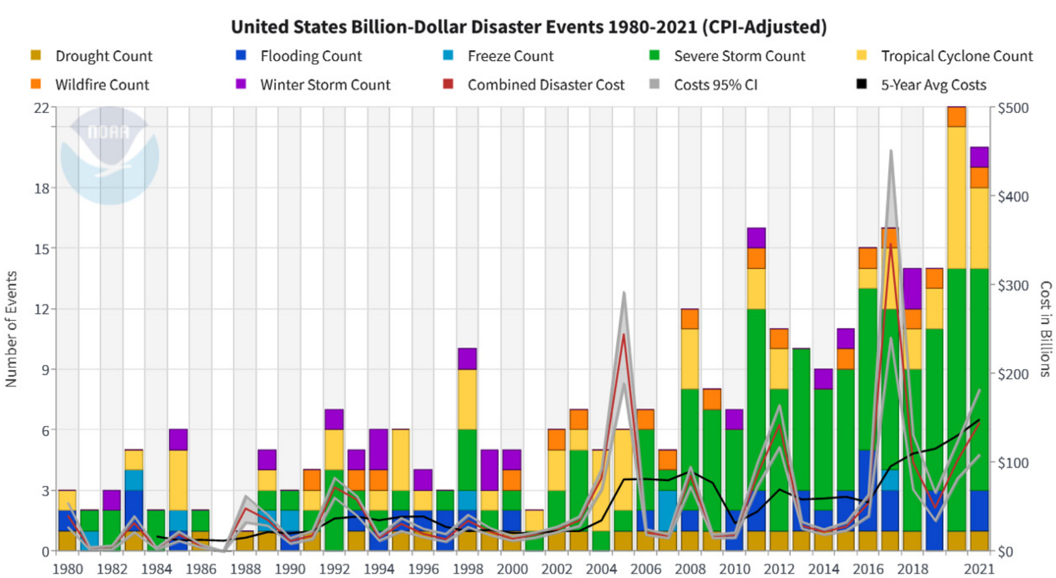


Figure 1: *Billion-Dollar Disaster Events, from NOAA*

Roadmap to Carbon Neutrality

A key initiative to reduce the industry's overall carbon emissions is spearheaded by the Portland Cement Association (PCA). Representing manufacturers of the most widely used cement type, portland cement, the PCA has defined the industry's efforts in its Roadmap to Carbon Neutrality. As detailed in the Roadmap, America's cement manufacturers have committed to the goal of reaching carbon neutrality throughout the cement-concrete-construction value chain by 2050.

While some carbon neutrality initiatives in other industries focus on one aspect of a material's production, the Roadmap differentiates itself by encompassing the entire value chain–a vitally important aspect of achieving sustainability. The value chain looks beyond the production of the material and takes its use phase into consideration, as well as the end of its life. If only one segment of a value chain is committed to sustainability and the others are not, the efforts are ineffectual.

The value chain for concrete includes five stages, beginning at the cement plant and extending through the entire life cycle of the built environment to incorporate the circular economy. According to the PCA, this approach to carbon neutrality leverages relationships at each step of the value chain, demonstrating to the world how this industry can successfully address climate change.

The five links in the value chain include:

- Production of clinker, the key chemically reactive ingredient used to produce cement.
- Manufacture and shipment of cement, which binds a concrete mixture together.
- Production of concrete by mixing cement with other ingredients (primarily aggregates and water).
- Construction of the built environment, including concrete pavements.
- Carbonation, where concrete structures absorb CO_2.

The Roadmap calls for accountability at each step of the value chain from the first production stages, to the final reuse and recycling phase. All segments of the value chain must work together. The Roadmap provides direction and incentives that urge action, and the concrete pavement industry is in full alignment with the Roadmap's objectives at every phase. Ultimately, calling for more concrete pavement projects creates a safe, reliable, cost-effective, sustainable, and resilient infrastructure network which achieves the industry's goal for net-zero CO_2 emissions by 2050.

Figure 2:
The Cement-Concrete Value Chain, from PCA Roadmap

The Importance of Life Cycle Thinking

While the Roadmap focuses on concrete's value chain, it also discusses the importance of life cycle thinking as an important component to having a long-term, sustainable system. The pavement life cycle (illustrated in **Figure 3**) begins with the upfront phases of pavement design, materials production, and construction, which make up the cradle-to-gate portion of the life cycle. This extends through the ongoing activities of pavement use, maintenance and preservation, and end-of-life phases to fully evaluate the pavement from cradle to grave. Life cycle thinking with a sustainability focus goes beyond the traditional evaluation of the economic impacts of the cradle-to-gate activities, to also include the environmental and social impacts of the pavement over its entire life cycle, from cradle to grave.

When properly done, designing for sustainability from a life cycle perspective allows designers to evaluate options and the impacts over the full life and from all phases to ensure that short-term gains do not come at the expense of long-term deficits. This results not only in better management of taxpayer funding, but also in reduced long-term environmental impacts and improved societal benefits.

Life cycle thinking begins with the development of design alternatives to accomplish the structural and performance objectives for a project. For a pavement, this includes developing the initial pavement designs and then defining the schedule of future activities required to maintain each design alternative for the project. Once those are defined for the different alternatives, the costs and environmental impacts of all activities over the life are estimated. Best-practice calls for including not only the direct agency expenditures and impacts, for example, construction or maintenance activities, but also the costs and impacts to the users of the systems based on the projected performance and stream of activities for each design alternative, more specifically the use and maintenance and preservation phases.

An important aspect to understand is that the initial decisions affect the use phase and maintenance and preservation activities, along with the associated costs and emissions, later in the pavement's life. That is, while it is important to focus on how the initial costs and upfront or embodied impacts can be reduced and is what most agencies and designers focus on because they are the easiest to define, often the most significant impacts are associated with utilizing the pavement itself. It is impossible to achieve sustainability and climate change goals without looking at the use and maintenance and preservation activities. Implementing life cycle thinking into the decision-making process provides decision makers the most flexibility to make significant sustainability improvements throughout the pavement's life.

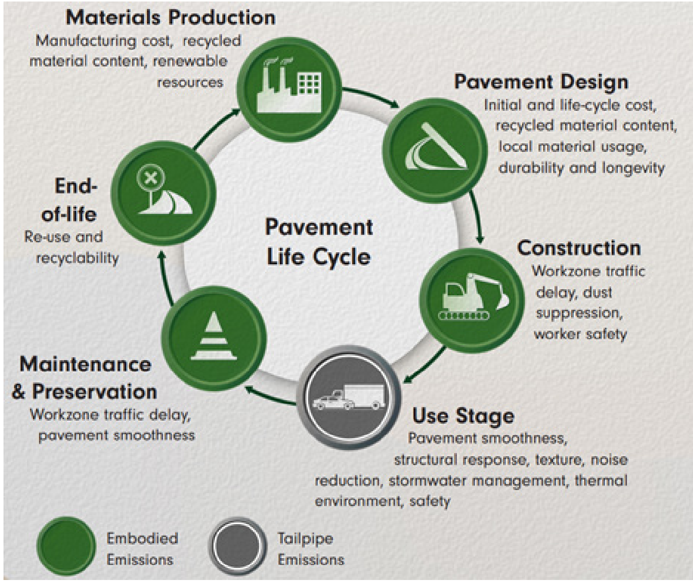


Figure 3:
Illustration of the Pavement Life Cycle, from FHWA

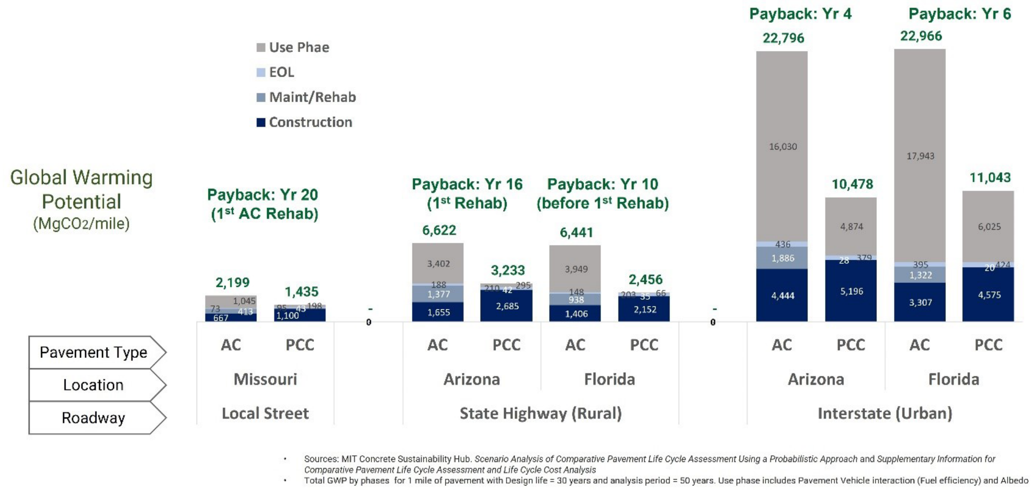


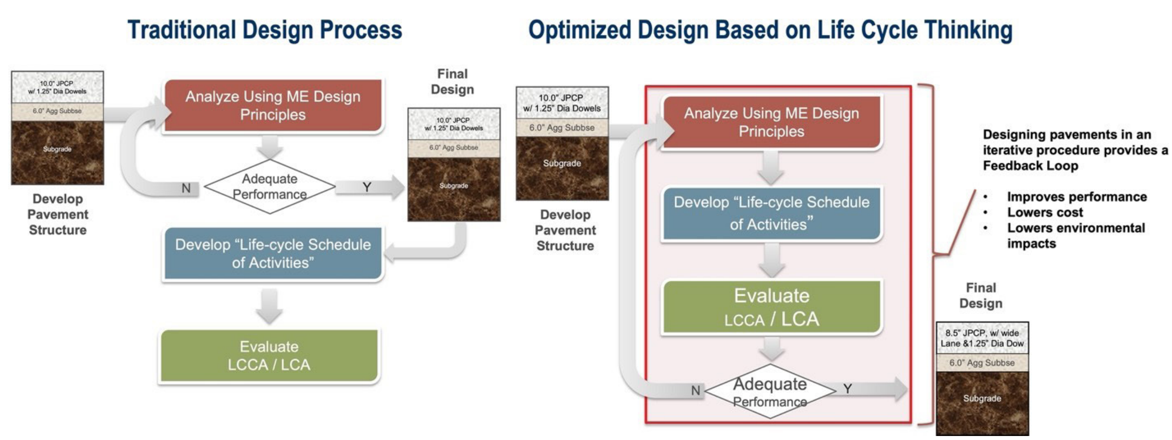
Figure 4: *Illustration of life cycle environmental impacts for various paving solutions across the country, from MIT CSHub*

Figure 4 highlights the initial and long-term environmental sustainability impacts for different pavement types across several locations. As can be seen from this example, concrete pavements can have higher initial impacts; however, when the entire life cycle is considered, the environmental implications and savings are significant. This trend is frequently seen with the economic and societal impacts as well, thus incorporating life cycle thinking into pavement-type selection leads to triple bottom line benefits, especially on high-volume, heavy-duty pavements where concrete excels.

The essential tools used for assessing life cycle sustainability are life cycle cost analysis (LCCA) and life cycle assessment (LCA). These tools used in conjunction with pavement design and analysis tools, like AASHTOWare's Pavement ME (Pavement ME), can be used together to evaluate and improve designs and their associated maintenance strategies to improve all aspects of sustainability. As illustrated in **Figure 5**, the greatest sustainability improvements will be made when this process iterates the pavement design and maintenance cycle development with feedback from life cycle tools.

There are numerous ways concrete pavements can be designed, optimized, and utilized to improve the sustainability of roadways, highways, and airfields; and many of these strategies are explored in the following sections. However, to truly evaluate and capitalize on all the benefits of concrete pavements, a life cycle approach to design and decision making is imperative.

Figure 5: *Design process to incorporate life cycle thinking, adapted from MIT CSHub*



Section Two: Economic Sustainability and the Role of Robust Materials Competition

While pavement sustainability is intended to look at economic, environmental, and social impacts of a pavement, most of the focus is currently being placed on the environmental portion. While this is critically important to address climate change and carbon reduction goals, it is important to recognize that every agency, municipality, city, and town are facing budget constraints and frequently make decisions based just on economic factors. To achieve sustainable, long-term road management success, decision makers must look for ways to simultaneously lower costs and lessen environmental impacts.

The importance of life cycle thinking has already been established, and one of the main evaluation tools is life cycle cost analysis (LCCA). While LCCA is supported by the Federal Highway and Aviation Administrations (FHWA and FAA, respectively) and commonly used across the country by state departments of transportation (DOTs), it is not utilized everywhere for all pavement type selections. Additionally, in locations where there is minimal data on concrete pavements the LCCA results are frequently heavily biased. In these cases, the best way to improve the economic side of sustainability is to recognize the benefits of industry competition.

Intra-industry competition is competition between firms that pave with different materials, versus inter-industry competition which is competition between firms that pave with the same materials. DOTs and municipalities can use intra-industry competition to maximize their budgets. When they use both asphalt and concrete pavements, they lower their pavement construction costs due to it bringing additional contractors, as well as additional suppliers (e.g. a second level of competition), into the supply chain that would not otherwise occur.

According to the Massachusetts Institute of Technology Concrete Sustainability Hub (MIT CSHub), state agencies that have sustained a consistent, competitive pavement market that uses both asphalt and concrete pavements for multiple years, ***pay lower unit prices for all paving materials.*** Their findings, illustrated in **Figure 7**, show that states with the highest level of competition have unit prices that are 29% lower for concrete, and 8% for asphalt.

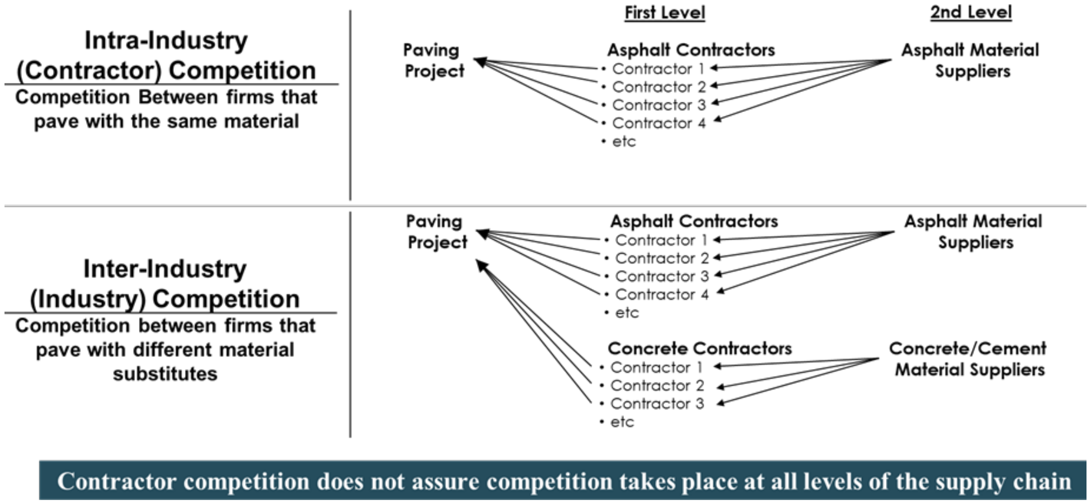


Figure 6: *Illustration of the multiple levels of competition that can be leveraged in pavement procurement, from J. Mack, L. Wathne, F. Mu,* Improving Network Investment Results by Implementing Competition and Asset Management in the Pavement Type Selection Process (2016)

Given the need to improve or expand road networks across the country, along with the sums of taxpayer funds expended, it is vital that agencies obtain maximum benefit from the limited funds available. By leveraging competition between industries, transportation agencies can get the most lane miles for their roadway budget and the highest rate of return for the public, which ensures taxpayer dollars are spent more effectively and efficiently.

While the impact will vary based on the particulars of any given market, there are no downsides to fostering two healthy industries to compete for paving projects. In areas where both pavement types are specified on a regular basis, it leads to benefits of healthy industries with more skilled personnel developed; construction quality improves; innovation is spurred; risks are reduced; and pavements improve. This in turn has environmental benefits as well because it helps mitigate the impacts of climate change through lower carbon usage over time due to less construction. Ultimately, benefits in sustainability and resilience are realized in local communities and around the globe.

Competition is the most powerful way to improve the economic sustainability of pavement systems. However, there are also many ways to directly improve both the upfront and long-term economic impacts of concrete pavements. Most of these have environmental benefits as well and are discussed in the following section.

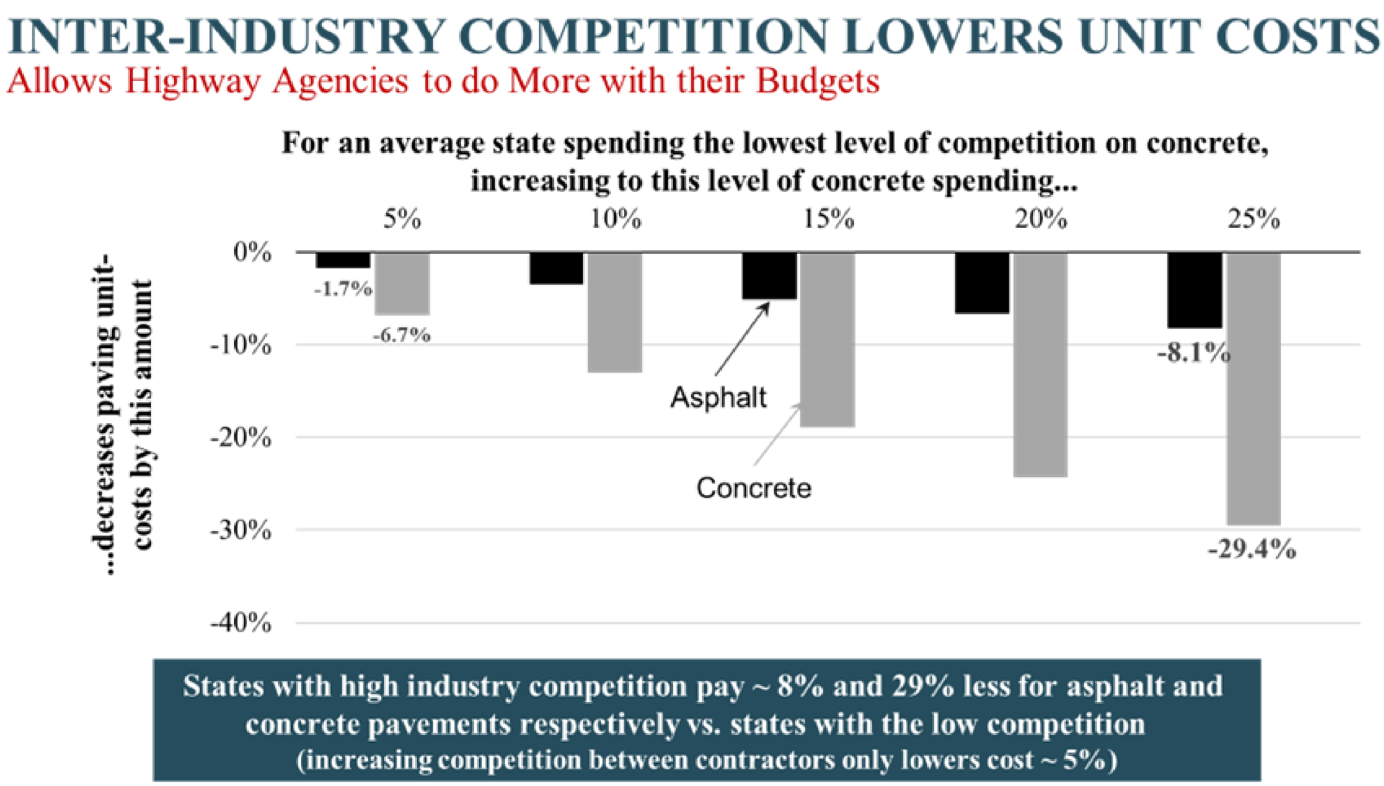


Figure 7:
The impact of increasing competition on material prices, from MIT CSHub

Section Three: Environmental Sustainability of Concrete Pavements

The environmental benefits of concrete pavements are considerable. Following PCA's Roadmap to Carbon Neutrality, the entire industry and value chain is working toward net zero carbon emissions. While industry invests in implementing and developing new technologies to meet the net zero goal, there are numerous, easy and minor alterations that can be implemented quickly to improve the environmental impact of concrete pavement systems throughout the life cycle. These activities fall under two primary categories: improving designs and reducing use phase impacts. These are introduced here and explored more thoroughly throughout this section.

Improving Designs

- Optimizing pavement designs
- Reducing cement's carbon footprint
- Optimizing concrete mix designs
- Improving resilience and durability (previously discussed in Section 1)

Reducing Use Phase Impacts

- Improving fuel efficiency
- Increased pavement albedo
- Take advantage of carbonation

Optimizing Pavement Designs for a Reduced Carbon Footprint

Just as quality pavement designs are key to achieving economic sustainability, they are also important to reducing the long-term environmental impacts of a pavement. Mechanistic-Empirical design tools, such as Pavement ME, can optimize a concrete pavement design to reduce "over design" and lower both the initial environmental impacts, as well as the life cycle environmental impacts.

Additionally, these tools can be used to evaluate how small changes to the design thickness, such as an additional half inch or inch of concrete pavement, or other design parameters, such as slab geometry, can result in as much as doubling the life of the pavement—with only slight additional economic and environmental impacts. These long-term benefits can only be evaluated and achieved with the previously introduced life cycle thinking design approach that utilizes LCCA, LCA, and quality pavement design tools in an iterative process.

As an example of the savings that optimization with life cycle thinking can deliver, **Figure 8** shows how a pavement design could be optimized to lower the environmental impact, yet still deliver the required performance. The original concrete design and rehabilitation schedule were developed from a state DOT's design manual. The optimized design was based on the life cycle thinking process outlined above, using Pavement ME in an iterative approach with LCCA and LCA, to develop the lower cost and lower environmental impact alternative.

Reducing Cement's Carbon Footprint with Blended Cements

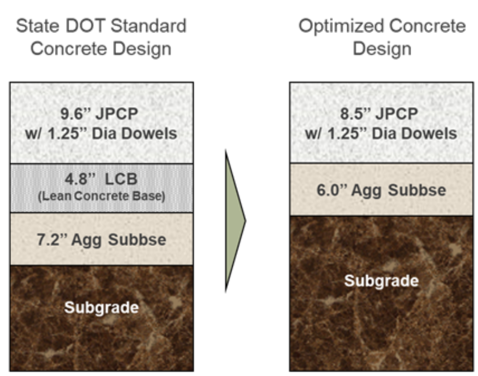
PCA outlines the path to reducing cement and concrete's carbon footprint in the Roadmap to Carbon Neutrality. This is important as the embodied environmental impact of cement and concrete is significant and is often the focus of the general public when it comes to concrete's sustainability. It is also the most prominent environmental factor captured in most Environmental Product Declarations (EPDs).

The first place to begin reducing the environmental impact of concrete used in pavements is with the ingredients of the concrete mixture. The ingredient with the most significant impact is cement. A simple way to reduce its impact—one that is currently being implemented—is to use portland-limestone cements (PLCs).

Portland-limestone cements have an increased amount of limestone in a cement blend that decreases carbon emissions with minimal effect on performance. This increase results in a decrease of up to 10% of the embodied CO_2 for the cement. PLCs can be used as a one-to-one replacement for conventional portland cement and have been used in concrete paving for over 15 years. This is a simple transition that can be implemented immediately to help reduce the carbon footprint of concrete.

Another option to reducing concrete's CO_2 emissions across the value chain is by reducing the amount of clinker required to produce cement. One way to achieve this is by incorporating supplementary cementitious materials (SCMs) into other types of blended cements beyond PLCs.

According to the PCA Roadmap, currently, most cements have a clinker to cement ratio of more than 90%. The remaining material, gypsum, limestone, and processing additions can be partially replaced with SCMs (fly ash, slag, silica fume and other materials), which directly reduces the CO_2 that comes with clinker production. Reducing the clinker amount 15% reduces the amount of CO_2 by 15%. Furthermore, using proper amounts of SCMs can improve durability and address the harmful chemical reactions caused by some aggregates. Cement companies are committing to decreasing the amount of clinker required by incorporating SCMs in the manufacture of cement.



	Original DOT Schedule		Pavement-ME Design	
	LCA (tons CO_{2e})	LCCA (NPV $)	LCA (tons CO_{2e})	LCCA (NPV $)
Initial Const.	**3,954**	**$3,147,585**	**3,063**	**$2,256,638**
Pavement	*2,860*	*$2,229,803*	*2,803*	*$2,021,307*
LCB	*781*	*$644,902*	*--*	*--*
Agg Subbase	*313*	*$272,880*	*260*	*$235,331*
Rehabilitation	**479**	**$911,663**	**54**	**$315,798**
Carbonation	**(123)**		**(87)**	
PVI-Deflection	**604**		**704**	
PVI-Roughness	**1,912**		**2,110**	
Total	**6,826**	**$4,059,248**	**5,844**	**$2,572,437**

Optimization reduced the initial construction GWP by **890 tons (22.5%)** and the life cycle GWP by **980 tons (14.3%)**

Optimization reduced the initial construction costs by **$890k (28.3%)** and the life cycle cost **$1.48M (36.6%)**

Figure 8: *Design optimized with life cycle thinking approach from Mack, Akbarian, Ulm, et al (2012)*

Reducing Concrete's Carbon Footprint with Performance-Engineered Mixtures

The next key step in reducing the environmental impact of concrete pavements is to reduce the carbon footprint of the concrete mixture itself by creating performance-engineered mixtures (PEM).

PEM was developed to better design and evaluate concrete mixtures and to ensure achievement of long-term durability, to enable the material itself to last as long as the pavement is designed for. The PEM Transportation Pooled Fund was established to develop and bring newer technologies to broader use and deliver on the promise of concrete durability. The Federal Highway Administration (FHWA), 19 state DOTs, and four national associations representing the concrete pavement industry came together to form the coalition funding the PEM project.

There are numerous benefits associated with the use and implementation of PEM. Some of the benefits include:

- Improved testing for true durability properties.
- Improved specifications focusing on desired material properties.
- Improved long-term durability.
- Improved mix development for local materials.
- Improved mix constructability for contractors.
- Improved mix optimization.

Many of these result in environmental benefits and a reduced environmental footprint for the concrete used in pavements. The focus of the PEM effort is to achieve and deliver on long-term durability, which aligns with life cycle thinking. Additionally, the PEM process better utilizes local materials without affecting performance. This can greatly reduce the distance materials are hauled.

Perhaps the most important sustainability aspect of PEM is optimization of the concrete mixture itself, in the form of optimized aggregate gradation (utilizing locally available materials), optimizing the cement content, and optimizing the use of SCMs. All of these can have huge impacts on reducing the embodied carbon footprint and the cost of concrete pavement mixtures, while also delivering durable concrete.

Figure 9 illustrates the easily achievable reductions in environmental impacts by utilizing strategies such as implementing PLCs, utilizing SCMs, and using PEM to optimize the aggregate gradation relative to using a non-optimized mixture that only utilizes ordinary portland cement.

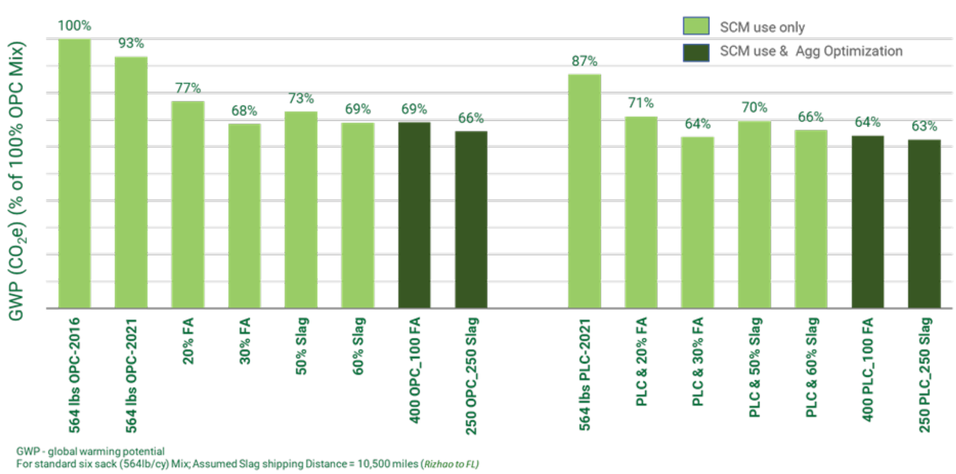


Figure 9:
Impact implementing sustainable practices such as the use of PLCs, SCMs, and optimizing aggregate gradations with PEM, from Jim Mack, CEMEX

Use Phase Impacts

Pavements and other infrastructure assets typically have significant upfront environmental and economic impacts, but it is essential to understand and remember that these assets are long-term investments. They are meant to stay in place and be used for decades. During their service life, they will be continuously utilized by the public. The public's use of a pavement has associated economic and environmental impacts as well. While the user's economic burden can be placed solely on the user, the environmental burden impacts everyone. For this reason, it must be understood that the pavement design and maintenance decisions made by engineers can have a significant impact on the environmental burden associated with using and maintaining the roadway itself.

Concrete pavements, because of their inherent properties of strength, stiffness, brightness, and durability, significantly reduce a pavement's use phase impacts. These savings come from:

- Reduced pavement vehicle interactions (texture, smoothness, stiffness)
- Increased albedo or reflectivity, which lowers urban heat island and increases radiative forcing
- Carbonation of the concrete

The Role of EPDs in Sustainability

Announced in May 2022, FHWA's Climate Challenge urges state DOTs and industry to take steps toward carbon neutrality, including embracing and utilizing EPDs and LCA. According to the PCA Roadmap, EPDs are an intermediate accounting of embodied CO_2 showing the upstream environmental impact sometimes referred to as the cradle-to-gate impact of a material.

EPDs provide upstream sustainability data that designers can use to conduct a full LCA of a structure, such as a pavement or roadway, to learn the best way to lower the total CO_2 of the final product. While EPDs can be useful for comparing similar products and potentially reducing embodied impacts, their limited scope means that they are a small part of the life cycle thinking in pavement design and material choice selections.

Instead, an LCA offers the optimal approach for assessing the overall sustainability of design systems, as it captures the environmental impacts throughout the life cycle of a pavement and can include effects from using the pavement, which can outweigh all other considerations. When an LCA with all life cycle phases is considered, concrete pavements are often the most sustainable solution.

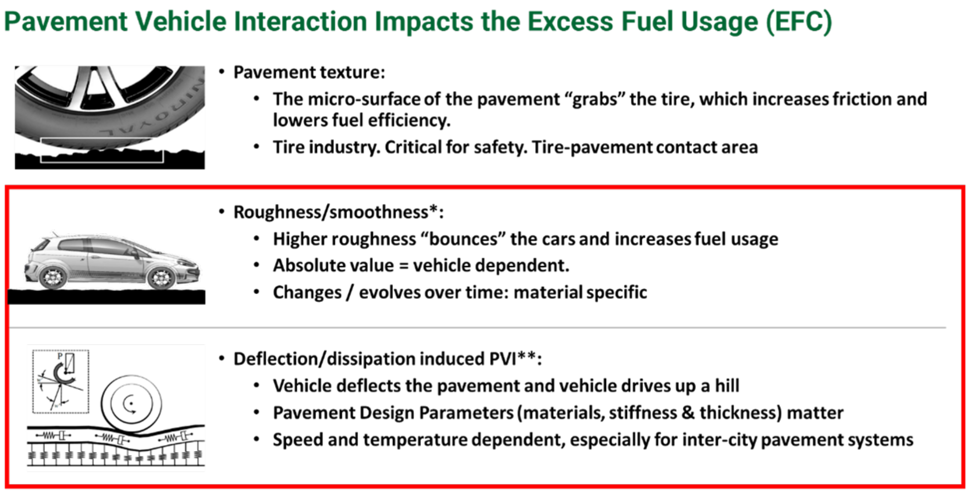


Figure 10: *Pavement Vehicle Interaction Impacts, from MIT CSHub*

Pavement Vehicle Interaction

Pavement vehicle interaction (PVI) is the increased or excess rolling resistance that occurs between the vehicle and the pavement on which it is driving. This excess rolling resistance increases the excess fuel consumption (EFC), defined as fuel consumption beyond what is required to move a vehicle, and causes additional CO_2 emissions. It is one of the most significant use phase impacts for pavements, especially on higher volume roadways with a significant amount of truck traffic.

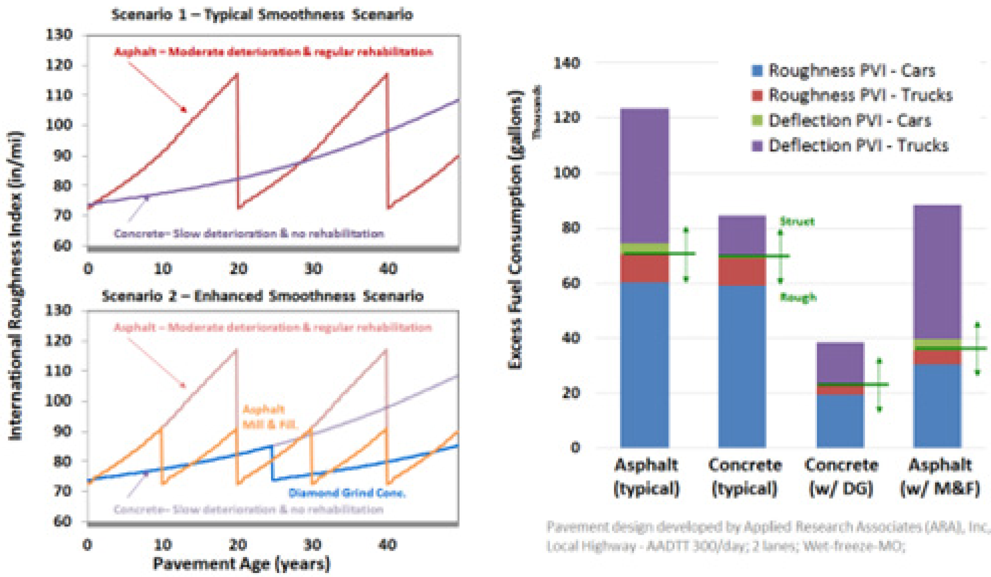
PVI has three primary factors that impact EFC: pavement texture, smoothness or roughness, and stiffness. While the pavement texture can have a large impact on the EFC associated with the use of the pavement, it also impacts safety, so there is a balance between low texture for low fuel usage and enough texture for safety.

Changes in the other two aspects, smoothness and stiffness, can result in large reductions in EFC and environmental impacts. The smoothness of a pavement is one of the main things the travelling public notices while driving. While rough pavements can be a nuisance to drivers, they also require greater fuel usage to traverse as the vehicle's suspension is engaged to deal with the bouncing of the vehicle. The rougher a pavement is, the greater the EFC for the travelling public, and the greater the environmental footprint associated with using the pavement. Thus, it is important to build smooth pavements that can maintain their smoothness throughout the life of the pavement.

Likewise, the stiffness of a pavement can also have a significant impact on the EFC of the vehicles using it. When a vehicle drives on a pavement, the pavement deflects, and the vehicle must continuously drive uphill to overcome the deflection. Stiffer pavements, such as concrete pavements, deflect less under the weight of the vehicles, especially under heavy trucks, and the lower deflection reduces the excess fuel consumption. This is one of concrete pavement's biggest advantages as it is inherently about 10 times stiffer than asphalt pavements.

The best performing pavements will be ones that are smooth and stiff. Concrete pavements are stiffer and remain smooth longer, which significantly reduces the PVI-related environmental impacts of utilizing the roadway. This can be further reduced by evaluating and utilizing life cycle thinking to optimize maintenance and preservation strategies, such as diamond grinding to improve concrete pavement smoothness, as illustrated in the example in **Figure 11**.

Figure 11: *Example of contributions to EFC from roughness and deflection based PVI, from MIT CSHub*

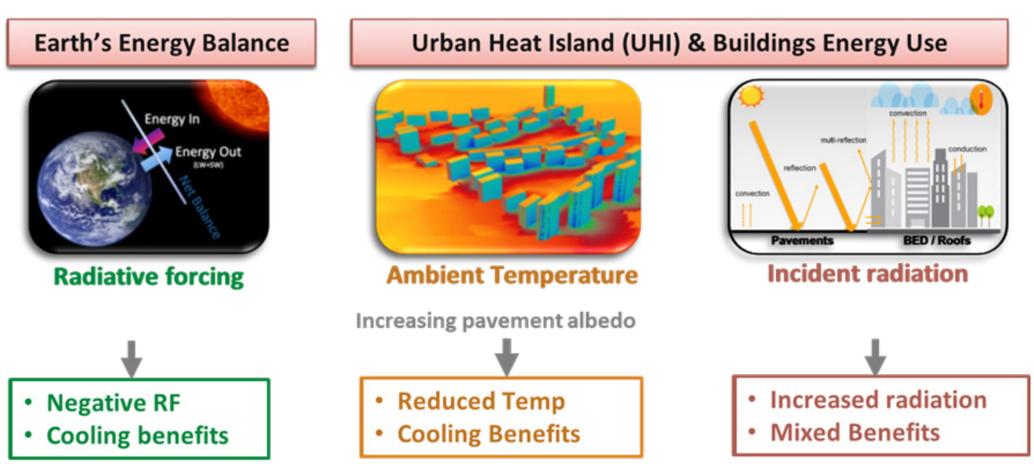


Albedo and Highly Reflective Surfaces

Albedo is the measure of the fraction of solar energy reflected by a surface. Lighter color surfaces reflect light and have a high albedo (maximum = 1), while dark surfaces absorb light and have a low albedo (minimum = 0). Choosing pavements with high albedo helps mitigate climate change and global warming potential by two major mechanisms:

1. **Radiative Forcing (RF)** – A measure of the Earth's energy balance. It is the difference between the amount of energy that enters the Earth's atmosphere and the amount of energy that radiates out into space. Increasing albedo radiates more energy out from the Earth and has a cooling effect.
2. **Urban Heat Island (UHI) and Urban Building Energy Use** – Increasing albedo decreases the ambient air temperature due to UHI. However, it can increase the incident radiation reflected from pavements to buildings, which impacts a building's cooling and heating requirements. Depending on location, climate, urban geometry, building properties, energy grid, etc., the net effect on building energy use can either be positive or negative. Note this is not a phenomenon that occurs in rural areas.

Figure 12: *Concrete pavement albedo impacts, from MIT CSHub*



Maximizing Radiative Forcing Impacts

Because the Earth has an albedo of ≈ 0.3 to 0.35, building a pavement that has a different albedo will impact the radiative forcing and changes the amount of solar radiation that is reflected into space. This is where concrete has a large advantage. A concrete pavement's albedo starts out light (≈0.40 for new pavement) and darkens over time (≈0.2 for old pavements). Asphalt pavements start out dark (≈0.05 for new) and lighten over to time (≈0.15 for old). In addition, when the pavements are rehabilitated, either through diamond grinding for concrete or asphalt overlays for asphalt, the pavements go back to their original albedo (≈0.40 for concrete and ≈0.05 for asphalt).

The takeaway is that concrete pavements always have a higher albedo than asphalt, which means there is a significant potential for pavements to reduce environmental impacts and mitigate climate change by using higher albedo concrete solutions.

Researchers at MIT's CSHub have quantified global warming potential (GWP) savings related to increases in pavement albedo and found that if all urban and rural roads in the continental United States were converted to pavements with higher light reflectivity, GWP savings would exceed 17 million tons of CO_2 emissions per year -- equivalent to removing roughly 3.7 million vehicles from our nation's roads for one year. In Texas alone, a 0.2 albedo increase to all urban and rural roads would create an estimated 1,574 kilotons of CO_2-equivalent savings per year, akin to removing more than 340,000 passenger vehicles from the road for a year.

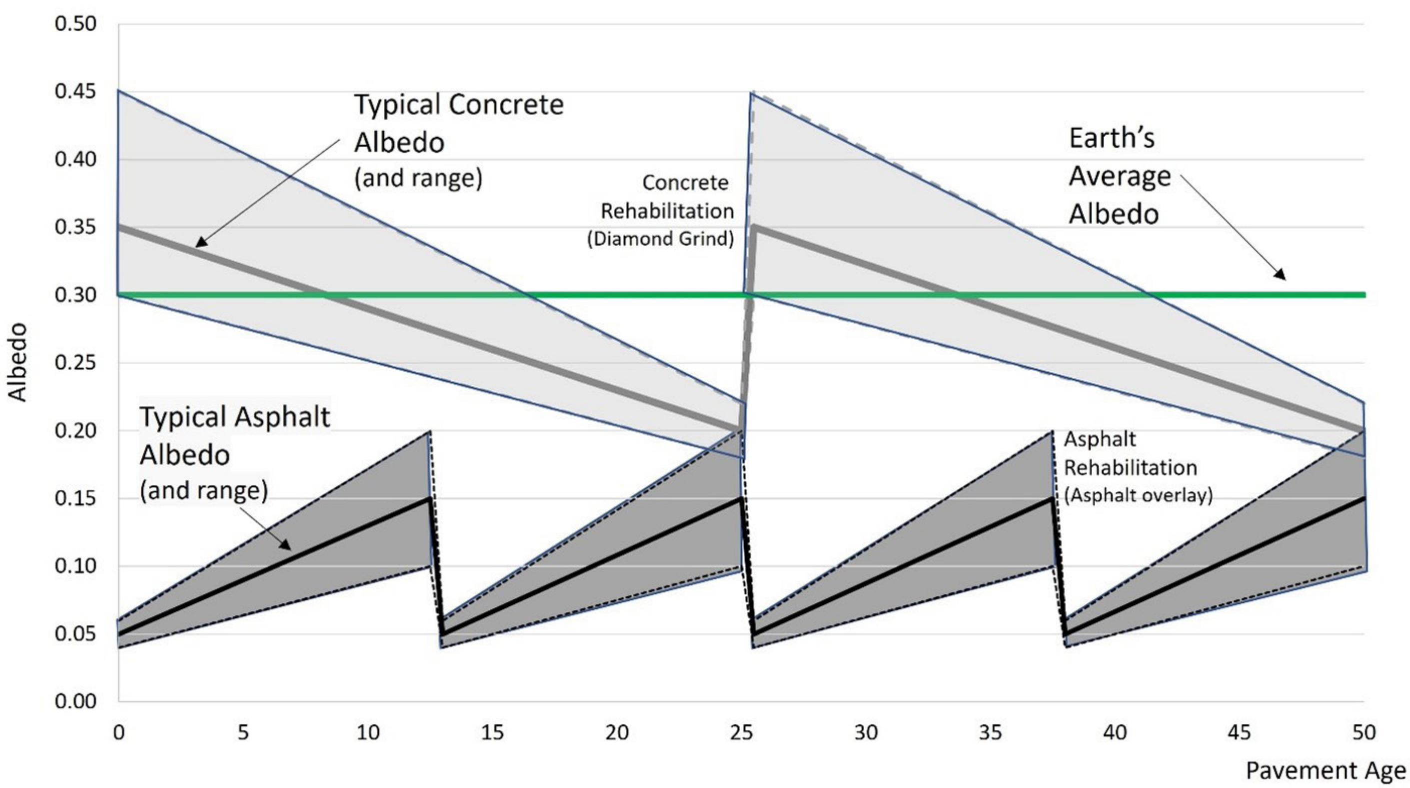


Figure 13:
Typical albedo profile for pavements, from Jim Mack, CEMEX

Minimizing Urban Heat Islands

In addition to the radiative forcing impacts, concrete pavement's high reflective properties also reduce UHI impacts because they reflect the sun's rays rather than absorbing them and re-releasing heat. In 2021, the International Grooving and Grinding Association and ACPA conducted infrared testing comparing temperatures throughout a 24-hour period for diamond ground concrete and asphalt-rubber-surfaced pavements in the Phoenix area.

The project evaluated two sections of the Phoenix freeway system. Via drone technology, researchers captured infrared imaging during live traffic and evaluated the impact of convection cooling from the moving vehicles. The study found that even with the cooling impact of the traffic, the asphalt rubber surface remained hotter than the concrete pavement throughout the course of the entire day. The asphalt was found to range from 2 to 6 degrees Fahrenheit hotter than the adjacent concrete pavement travel lanes throughout the day.

The study confirms that concrete maintains a cooler temperature than alternate pavement materials, and the higher temperatures of alternate materials contribute to the UHI effect. In the Phoenix area alone, an MIT case study found that the freeway system could reduce more than 2.7 million tons of CO_2-equivalent emissions by having an exposed concrete surface.

Studies have demonstrated that enhancing albedo can improve the sustainability aspects without the downside of environmental damage because it can, to some extent, mitigate or delay some of the consequences of warming from CO_2 emissions. While these advantages are inherent to concrete pavements, some areas are trying to replicate concrete's albedo and UHI benefits on asphalt pavements by painting the surface gray.

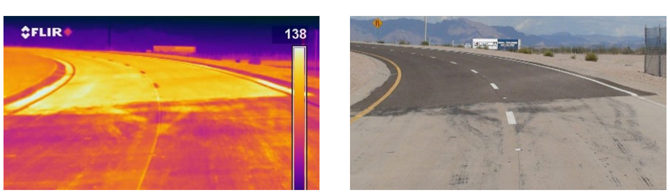


Figure 14:
The light color of concrete pavement reduces surface temperatures and mitigates UHI impacts

Carbon Dioxide Absorption

One of concrete's unique properties is its ability to function as a CO_2 sink for the planet. As concrete pavement ages, it absorbs carbon dioxide, helping to reduce the amount of CO_2 in the atmosphere through a process called carbonation.

MIT CSHub researchers investigated the carbon absorption of pavements throughout the United States. Published in Resources, Conservation and Recycling, January 2021, the article describes the carbonation process:

> *Just along concrete's gray surface, a chemical reaction is occurring. Known as carbonation, this reaction forms calcium carbonate, a benign chalk-like material, but it can also affect climate change. That's because calcium carbonate forms when CO_2 from the air reacts with water in concrete pores, and then with calcium compounds in concrete — meaning that concrete is a potential carbon sink.*

Thousands of simulations were used in the MIT CSHub research to predict how uncertainties would likely play out over the span of a 30-year analysis period. The predictions were then used to calculate the potential carbon uptake in each state based on the road conditions, maintenance actions, budgets, and road lengths.

Throughout the United States, the total amount of CO_2 that could be sequestered in concrete pavements is significant, the research suggests. In total, the study found that 5.8 million tons of CO_2 could be sequestered, with 2.8 million tons of CO_2 coming from the use phase and 3 million tons of CO_2 coming from the end-of-life phase. The study finds that the carbonation process could offset 5% of the CO_2 emissions generated from cement used in pavements across the United States.

Research by Anderson et. al shows that concrete's rate of sequestration decreases with time. This happens because calcium carbonate begins to fill up void spaces in the concrete and slows its uptake of CO_2. The carbonated surface can be removed, exposing uncarbonated concrete and beginning the carbonation process anew. The simplest way of doing this is by diamond grinding—a technique that is commonly performed as part of pavement preservation. It has many benefits beyond renewing the concrete's ability to carbonate, including keeping the road smooth and improving PVI as previously discussed. When states cover concrete pavement with asphalt overlays, carbonation is completely halted.

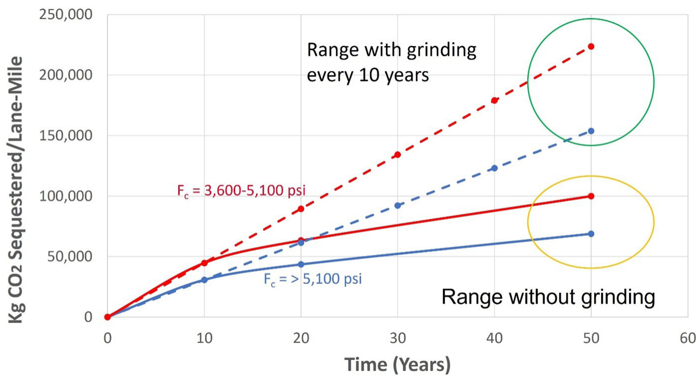


Figure 15:
Impact of regular diamond grinding on projected carbonation over a 50 year life, from Dr. Thomas Van Dam, NCE

Additional Strategies to Improve Concrete Pavement's Evironmental Sustainability

Most of the strategies to improve concrete pavement's environmental sustainability that have been presented thus far have been focused on either the pavement design and materials phases (improving designs approaches) or on reducing the use phase impacts. This is primarily because these are the most impactful things that can be done to improve the sustainability of concrete pavements throughout the life cycle. The impacts of the other phases, including construction, maintenance and preservation, and end-of-life, are typically relatively small for concrete pavements. However, improvements in all phases are necessary.

The maintenance and preservation phase has been briefly discussed in this section, with references to the main treatment for concrete pavements being diamond grinding. As previously discussed, this has numerous benefits from restoring the smoothness of the pavement (reducing PVI related impacts), to resetting the albedo of the pavement (improving the RF and UHI related impacts) and renewing the carbonation process (increasing the CO_2 that can be absorbed). These impacts can be optimized through the life cycle design approach to improve the sustainability of concrete.

The last two phases where sustainable improvements can be made include the construction and end-of-life phases. Contractors regularly improve the construction phase impacts through optimized planning and reducing transportation of materials wherever possible. The end-of-life phase can be optimized most by continuing to utilize the in-place structure for as long as is feasible. This means utilizing long-life designs, such as concrete pavements and overlays, that do not need to be regularly replaced. When the pavement must be replaced, one strategy that can improve both the construction and end-of-life impacts is recycling.

Recycling

Concrete is 100% recyclable and often re-used on the same project site. Opportunities to recycle concrete on grade reduce truck hauling, further improving the carbon footprint of a concrete pavement project.

Concrete ranks as the most recycled material in the United States. Approximately 140 million tons of concrete are recycled each year. Additionally, when concrete is recycled, it greatly accelerates the carbonation process. Concrete pavements do not have to be recycled as frequently as alternate paving materials since they last longer. When recycled, concrete has a variety of uses, including base material, aggregate in new concrete, and granular fill.

Section Four: Society and Concrete Pavements

Social sustainability identifies and manages the impacts, both positive and negative, of industry on people. It also includes environmental justice, which refers to the fair treatment and meaningful engagement of all people regarding environmental protection. For example, equitable efforts to preserve surrounding green areas should be provided to all neighborhoods. Additionally, all neighborhoods and all people deserve equal infrastructure updates to make areas more livable and accessible to work opportunities.

Social sustainability starts with recognizing the need for pavements and roadways to move people and goods from one place to another. A pavement's performance is vital to our country's well-being and social sustainability, which is why designing with a life cycle approach is critical to keep the pavement in good condition for the travelling public. Concrete pavements represent a socially sustainable choice due to their long-life and good performance with minimal traffic disruption due to maintenance, in addition to their use phase benefits to the surrounding community.

Rideability and Improved PVI

A concrete pavement's texture is engineered to stay smooth and quiet throughout the pavement's life. This not only supports a pleasant driving experience, but also reduces wear and tear on vehicles and decreases fuel expenditures and emissions by the travelling public by lowering rolling resistance. Additionally, the smoothness and noise properties related to a concrete pavement can be easily restored through proper preservation, including diamond grinding.

Health and Safety

All pavements must deliver a safe roadway for the travelling public and those working on the roadway. When designed and constructed appropriately, concrete pavements deliver a smooth and durable surface with minimal issues for decades, which makes concrete safe for the travelling public. Additionally, the minimal repairs and maintenance needed to maintain concrete pavements mean fewer work-zones and construction related incidents. Concrete can last 30 years or more before a maintenance cycle may be needed to restore smoothness which can help reduce the required work zones throughout the life cycle.

Concrete pavement's higher albedo has many societal benefits beyond the environmental benefits previously discussed. The higher light reflectivity associated with concrete's albedo provides health and safety benefits, as a brighter environment improves visibility and therefore reduces the potential for traffic-related incidents. Additionally, in reducing UHI and increasing RF, concrete pavements can also help mitigate the public health effects caused by extreme heat events and cool the surrounding area. Creating cooler pavements is also important for constructing roadways where workers can be exposed to extreme temperatures.

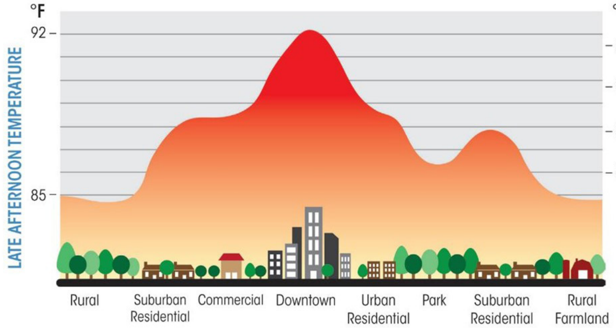


Figure 16:
Concrete's high albedo can reduce UHI impacts and surrounding temperatures, from Clean Air Partnership

Section Five: Conclusion

Sustainability is a necessary priority as America's infrastructure is maintained, rehabilitated, and expanded. Decision-makers must consider the elements of economic, environmental, and social sustainability when choosing pavement types. An understanding of the important role resilience plays in making infrastructure truly sustainable is vital. A system cannot be sustainable if it is not also resilient. Designing with a life cycle approach can help ensure that pavements are both resilient and sustainable across all three categories (economic, environmental, and social).

Concrete provides the most sustainable, resilient choice for pavement systems. Its long lifespan provides the greatest economic value over the long term for taxpayers and end users. Its environmental benefits are many, including improved fuel efficiency, high albedo which improves the earth's energy balance and Urban Heat Island, both of which lead to cooling impacts and CO_2 reduction, and CO_2 absorption. Additionally, the concrete pavement industry and others across the concrete value chain are working together to implement the PCA's Roadmap to Carbon Neutrality, with a goal of achieving net zero carbon emissions by 2050.

There are numerous ways to immediately decrease the embodied and long-term environmental impacts of concrete pavements, including optimized thickness designs, implementation of low-carbon cements, and utilization of PEM. For society, concrete pavement's sustainability benefits create safer, higher-performing roads, contributing to an equitable future for communities. Choosing concrete pavement for the nation's infrastructure is ultimately the most responsible choice to deliver sustainability today while ensuring future generations can meet their own needs.

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