TechBrief

APRIL 2016 FHWA-HIF-16-013

STRATEGIES FOR IMPROVING SUSTAINABILITY OF CONCRETE PAVEMENTS

ABSTRACT

This Tech Brief summarizes guidance to the pavement community on sustainability considerations for concrete pavement systems, as presented in greater detail in the recently published *Towards Sustainable Pavement Systems: A Reference Document* (FHWA 2015). Sustainability considerations throughout the entire pavement life cycle are examined (from material extraction and processing through the design, construction, use, maintenance/rehabilitation, and end-of-life phases) and the importance of recognizing context sensitivity and assessing trade-offs in developing sustainable solutions is emphasized.

This Tech Brief focuses exclusively on sustainability considerations associated with concrete-surfaced pavement structures and the materials used in their construction. For the purposes of this document, all permanent surfaces constructed with hydraulic cement concrete are generically referred to as "concrete" pavements.

The primary audience for this document is practitioners doing work within and for government transportation agencies, and it is intended for designers, maintenance, material and construction engineers, inspectors, and planners who are responsible for the design, construction and preservation of the nation's highway network.

INTRODUCTION

An increasing number of agencies, companies, organizations, institutes, and governing bodies are embracing principles of sustainability in managing their activities and conducting business. A sustainable approach focuses on the overarching goal of considering key environmental, social, and economic factors in the decision-making process. Sustainability considerations are not new and, in fact, have often been considered indirectly or informally. In recent years, significant efforts have been made to quantify sustainability effects and to incorporate more sustainable practices in a systematic and organized manner.

A companion Tech Brief (FHWA 2014) presents a summary of the application of sustainability concepts to pavements. It provides an introduction to these concepts and how they are applied as best practices in the industry, focusing on current and emerging technologies and trends.

A sustainable pavement is one that achieves its specific engineering goals, while, on a broader scale, (1) meets basic human needs, (2) uses resources effectively, and (3) preserves/restores surrounding ecosystems. Sustainability is context sensitive and thus the approach taken is not universal, but rather unique for each pavement application. Furthermore, a "sustainable pavement" as defined here is not yet fully achievable. Today it is an aspirational goal to be worked towards, and ultimately achieved at some point in the future as sustainability best practices continue to evolve.

This Tech Brief, highlights "sustainability best practices" for concrete pavements, which are considered to be processes, actions, and features that advance the state of the practice towards more sustainable pavements. Specifically, "sustainability best practices" are those that either (1) go above and beyond required regulatory minimums or current standard practice, or (2) show innovation in meeting those minimums and standards. As described here, these sustainability best practices do not achieve sustainability, but they are improvements on current common practice and represent progress towards sustainability.

As a system characteristic that encompasses economic, environmental, and social dimensions, sustainability is necessarily the highest level consideration for an infrastructure system and not just an added feature. Simply put, sustainability means "consider everything." Other considerations (e.g., safety, conservation, ecosystem health, education, open space) are an expression of (1) various sustainability components, (2) an order of precedence for those components, and (3) a plan to operationalize those components.

In order to better understand the many facets of pavement sustainability, it is essential to consider the entire pavement life cycle (shown in figure 1), which can be divided into the following phases: production of materials, pavement design, construction, use, maintenance and preservation, and end of life. This Tech Brief introduces each of these phases, describes their interrelationships, and discusses the processes that may take place in each, as well as their impacts on sustainability. Many of these processes are interrelated and can conceivably be included in several different phases; however, each process will be addressed primarily within the discussion pertaining to the phase with which it is most closely associated.

- *Material Production*. Material production includes all processes in the acquisition (e.g., mining and crude oil extraction) and processing (e.g., refining, manufacturing and mixing) of pavement materials.
- *Design*. The design stage refers to the process of identifying the structural and functional requirements of a pavement for given site conditions (i.e., subgrade, climate, traffic, existing pavement structure, etc.), as well as the determination of the pavement structural composition and accompanying materials. It includes new pavement, rehabilitation and reconstruction.
- *Construction*. The construction stage includes all processes and equipment associated with the construction of the initial pavement.

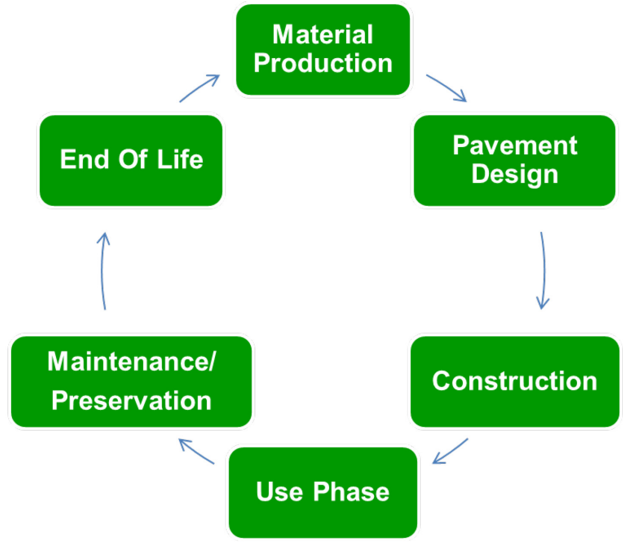


Figure 1. Pavement life-cycle phases.

- *Use Phase*. The use phase refers to the operation of the pavement and its interaction with vehicles, people, and the environment.
- *Maintenance/Preservation*. These are activities applied at various times throughout the life of the pavement that maintain its overall serviceability.
- *End of Life*. The end of life refers to the final disposition and subsequent reuse, processing, or recycling of the pavement after it has reached the end of its useful life.

SUSTAINABLE STRATEGIES FOR SELECTING AND USING MATERIALS IN CONCRETE PAVEMENTS

The concrete material phase encompasses the extraction and processing of the raw materials, transportation to the plant, the concrete mixture design and proportioning, as well as the plant operations to the point where the material is placed in trucks for transportation to the project site. Some typical sustainability questions that arise with regards to pavement material decisions include:

- Does the improved pavement system performance associated with the use of longer lasting materials offset the impacts of higher costs and possible higher production- and transportation-related impacts?
- Does the use of a particular material increase the variability of pavement performance, thereby increasing the frequency of required repairs?
- Do specifications that limit the use of lower impact materials effectively reduce the risk of poor performance, or do they prevent the opportunity to improve overall project sustainability?

- For a selected life-cycle time period, what is the total life-cycle impact resulting from using a paving material only once versus using it multiple times?
- If a recycled, co-product, or waste material (RCWM) is considered for use in a pavement construction project, will the inclusion of the RCWM make the resulting material more difficult to recycle in the future?

These are just a few of the questions that transportation professionals often face when making material choices to improve the overall sustainability of a pavement over the life cycle.

Recycled, Co-Product, or Waste Materials. What's the Difference?

- *Recycled materials are obtained from an old pavement and are included in materials to be used in the new pavement. Common recycled materials include reclaimed asphalt pavement or recycled concrete pavement. Depending on the regional market, these materials would be "waste" if not recycled, ending up in a landfill.*
- *Co-products are derived as part of another process (often industrial but possibly agricultural) that brings value to the overall process. For pavement applications, some of the most common co-products result from the production of pig iron for steel making, including slag cement and air-cooled iron blast furnace slag aggregate.*
- *Wastes are materials that normally would be sent to a landfill, for which the cost of transport and processing is the only source of economic value. If the material has value beyond this, it is no longer considered a waste, but instead a co-product. In some regional markets fly ash can be categorized as waste, whereas in other markets it is clearly a co-product because it has economic value beyond the cost of transport and disposal.*

Cementitious Materials and Concrete Mixtures

Concrete (sometimes referred to as "hydraulic cement concrete" [HCC]) is a mixture of coarse and fine aggregate bound together with "glue" that is created when water is mixed with hydraulic cement. The hydraulic cement used today is most commonly a blend of portland cement (AASHTO M 85/ASTM C150), supplementary cementitious material (SCM), such as fly ash, slag cement, natural pozzolans, etc.), and ground limestone. Furthermore, chemical admixtures are almost always employed to modify the behavior of the fresh and hardened concrete, making it easier to place, enhancing its strength, and making it more durable.

Following water, concrete is humankind's most commonly used material, with roughly 1 yd^3 (0.75 m^3) of it produced annually for every person on the planet. As such, the economic, environmental, and societal impacts of concrete are huge. Furthermore, the cost and environmental impact of concrete is largely dependent on the amount of portland cement used, the manufacture of which consumes up to 74 percent of the energy and produces up to 81 percent of the greenhouse gas (GHG) emissions associated with the cement and concrete industry in the U.S. (Choate 2003).

Portland Cement

Portland cement is manufactured by pyro-processing raw materials, dominated by limestone, in a rotary cement kiln at high temperatures (2460 to 2640 °F [1350 to 1450 °C]). The consumption of fuel (which differs regionally, consisting of pulverized coal, natural gas, used tires, waste industrial oils and solvents, and, in some cases, biomass) is responsible for a portion of the GHG emissions in cement production, but more than half of the production-related GHG emissions are released due to the decomposition of limestone ($CaCO_3$) into lime (CaO) and carbon dioxide (CO_2) (EPA 2013; Van Dam et al. 2012). While cement kiln efficiency has improved dramatically over the last two decades (significantly reducing the energy needed for pyro-processing and the associated emissions) cement production was still responsible for approximately 0.5 percent of the U.S. total GHG emissions of CO_2e in 2013 (EPA 2015).

Supplementary Cementitious Materials

SCMs are materials that when blended with portland cement contribute to the properties of concrete through hydraulic or pozzolanic activity, or both (Kosmatka and Wilson 2011). Hydraulic activity occurs when the SCM chemically reacts with water, forming cementitious hydration products. Pozzolanic activity occurs in the presence of water when reactive siliceous or aluminosiliceous material in the SCM reacts with calcium hydroxide (a product of the hydration of portland cement) to form calcium-silicate-hydrate and other cementitious compounds, which generally improve concrete long-term strength and durability. SCMs that are commonly used in paving concrete include fly ash (specified under AASHTO M 295) and slag cement (specified under AASHTO M 302).

Fly ash consists of spherical glassy particles that are collected from the flue gases of coal-fired power plants. It varies in composition and mineralogy with the source of coal, how it is burned, and how the ash cools. Under AASHTO M 295, it is classified as either a Class C fly ash or a Class F fly ash. In general, Class C fly ash has higher calcium oxide content and can have both hydraulic cementitious and pozzolanic characteristics. Class F fly ash, on the other hand, typically has less calcium oxide and is primarily pozzolanic. The pozzolanic reaction helps mitigate ASR and sulfate attack so, in general, concrete made with Class F fly ash will have improved chemical durability over concrete made with pure portland cement or Class C fly ash. All fly ash tends to improve long-term strength and reduce permeability (which improves durability). Class C fly ash is typically dosed at 15 to 40 percent by mass of the total cementitious materials used whereas Class F fly ash is typically dosed at 15 to 25 percent for pavement applications (Taylor et al. 2006).

Slag cement is an industrial co-product from the smelting of iron in a blast furnace in which molten slag is quenched using water to form a glassy sand-like material containing amorphous oxides of calcium, aluminum, magnesium and iron. It is subsequently ground to a fineness that is similar to that of portland cement. It is slowly reactive in the presence of water or more vigorously when activated in water in the presence of calcium hydroxide, which is present in the pore solution of hydrating portland cement.

Slag cement is an attractive SCM for a number of reasons. For one, the typical dosage of slag cement is usually in the range of 25 to 35 percent of the total cementitious materials for paving concrete, although it can be used in even higher amounts (ACPA 2003). Furthermore, slag cement creates very light colored concrete that some find aesthetically pleasing and can produce a higher albedo concrete pavement that may help reduce the urban heat island effect. In addition, concrete permeability and chloride ion ingress are reduced when slag cement is used, and slag cement can be used to effectively mitigate ASR and sulfate attack.

Blended Cements

Blended cement is produced and sold by cement manufacturers that intergrind or blend portland cement with fly ash, natural pozzolans, slag cement, and/or limestone to produce binary (two-component) or ternary (three-component) systems as specified under AASHTO M 240, *Standard Specification for Blended Hydraulic Cements*. These materials are classified as Type IP (portland-pozzolan cement), Type IS (portland-slag cement), Type IL (portland-limestone cement) and Type IT (ternary blended cement containing portland cement and two additional SCM components). Typical portland cement replacement rates for blended cements are 10 to 12 percent for Type IL, 15 to 25 percent for Type IP, and 30 to 50 percent for Type IS (Van Dam and Smith 2011). The use of blended cements can significantly reduce CO_2 emissions compared conventional portland cement while improving concrete durability and long-term strength.

Aggregate Materials

Aggregates make up the largest share of the mass and volume in a pavement structure, whether used without a binding material (e.g., unbound subbase or base material), or as part of an asphalt or hydraulic cementitious bound layer. Although aggregates have relatively low costs and a low environmental impact per unit mass relative to other materials that are used in pavements, they can have a significant impact on pavement sustainability because they are consumed in such large quantities.

Aggregate used in unbound bases and subbases may be derived from natural sources or may be manufactured or derived from recycled pavement materials or other suitable demolition materials. Aggregate used in concrete may be derived from natural sources or may be manufactured or derived from recycled or even waste materials. From a sustainability perspective, it is convenient to combine manufactured aggregates with recycled materials into a RCWM category that includes the following:

- *Reclaimed asphalt pavement* (RAP), usually produced from the millings of an existing asphalt pavement. While the predominant use of RAP is in new asphalt pavement, RAP is also commonly used in aggregate bases, and coarse fractionated RAP (FRAP) is successfully used by the Illinois Tollway and others as coarse aggregate in concrete mixtures.
- *Recycled concrete aggregate* (RCA), created when concrete is purposefully crushed to create aggregates for use in subbase, base, or paving (asphalt or concrete) applications. RCA typically contains some unhydrated cement which, when exposed to moisture in compacted bases and subbases, can hydrate to produce base/subbase materials with increased stiffness and other improved properties when compared with those of virgin aggregates (Chai, Monismith, and Harvey 2009). When used as base or subbase, both the coarse and fine RCA are often used. RCA may also be used in new concrete mixtures, particularly in the lower lift of two-lift paving operations. In new concrete, it is most common to use only the coarse fraction of the RCA as the fines significantly increase water demand and may also have a disproportionately high concentration of chlorides if

recycled from pavements subjected to chemical deicing.

- *Air-cooled blast furnace slag* (ACBFS) is another material used as aggregate in concrete and unbound base and subbases.

The use of RCWMs continues to increase for economic and environmental reasons. A proper engineering evaluation must be done when using these materials in concrete paving mixtures to ensure that their properties do not negatively impact the fresh or hardened properties of the concrete. Several publications provide good guidance concerning the use of these materials (ACPA 2009; Van Dam et al. 2012; Morian, Van Dam, and Perera 2012; Smith, Morian, and Van Dam 2012; and Brand et al. 2012).

Major sustainability issues related to use of virgin aggregate in pavements include:

- Environmental damage caused by quarries and sand and gravel pits from which virgin natural aggregate are extracted, much of which can be mitigated through restoration when aggregate extraction has been completed;
- Transportation-related energy consumption and emissions from transportation, which are highly dependent on the mode of transport (marine, train or truck) and distance aggregate are moved; and
- Energy consumption and emissions from processing aggregates to improve them for use in pavement materials.

A major source of environmental burden associated with aggregate production is transportation. Aggregate must be transported from the source to the job site for unbound bases and subbases, and transported to the concrete or asphalt mixing plant and then to the project site. Transport-related impacts primarily involve the burning of fossil fuel-based fuels in trucks or other transport vehicles. The energy use and GHG emissions from transport can be larger than those from mining and processing, especially if trucks are used instead of more fuel-efficient transportation modes, such as rail or barges.

Aggregates in Concrete

In addition to the general aggregate sustainability considerations described previously, it is important to consider the impacts of aggregate properties (e.g., aggregate grading and durability) and the use of RCWMs on the sustainability of concrete paving mixtures. For example, aggregate grading has a profound effect on the amount of cementitious material needed to obtain the desired fresh and hardened properties of the paving concrete. A properly proportioned concrete paving mixture will often have an "optimized" aggregate grading that increases the aggregate volume through careful consideration of the particle size distribution. This allows for a reduction in cementitious material content while achieving the required fresh (workability, finishability, etc.) and hardened (strength and durability) properties. It is now common to find workable, strong, and durable concrete paving mixtures with total cementitious materials contents of 540 lbs/yd^3 (320 kg/m^3) or less, resulting in both economic and environmental savings compared to previous practices.

The importance of aggregate durability on the overall durability of concrete and pavement longevity cannot be overemphasized. In addition to meeting all the requirements of applicable AASHTO standards for concrete aggregates (i.e., AASHTO M 6 and M 80), the aggregate should meet applicable freeze-thaw durability and ASR reactivity requirements. The AASHTO provisional protocol PP 65-11, *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction* should be used to screen aggregates intended for use in paving concrete, and the use of SCMs, such as Class F fly ash or slag cement, should be used in ASR mitigation strategies if susceptible aggregates are to be used.

Strategies for Improving the Sustainability of Aggregate Use in Concrete Pavements

Strategies for reducing environmental impact from aggregates used in concrete pavement structures include:

- Reduce the use of virgin aggregate through increased use of RCWMs, increased aggregate and pavement durability, and increased pavement design life.
- Reduce the amount of cementitious materials used in concrete mixtures through the use of "optimized" (more densely graded) combined aggregate gradations.
- Reduce the impact of virgin aggregate acquisition and processing through improved mining practices.
- Reduce the impact of aggregate transportation through mode choice, greater use of locally available aggregates and RCWMs (without compromising performance requirements), and optimally located construction staging and processing areas.

Water Sources

Water is used in the concrete production process not only in the preparation of the concrete mixtures, but also in the washing of aggregates, wetting aggregate stockpiles, and cleaning of trucks and equipment. Decisions regarding concrete mixing water must consider the quality of the required water for each application, the impact of the water use on the environment, and economic factors (Van Dam et al. 2012). Technologies for using increasing amounts of "grey water" (obtained from washing concrete production equipment and trucks) in concrete mixtures are rapidly becoming more common and accepted, although grey water with high solid contents (i.e., >15 lb/yd^3 [8.9 kg/m^3]) can significantly impact concrete mixture water demand, setting time, compressive strength and permeability (Lobo and Mullings 2003).

Chemical Admixtures

Chemical admixtures are added during batching to modify the fresh or hardened properties of concrete. These modifications can enhance sustainability by improving the workability of the concrete, reducing water demand, and improving durability. Modern paving concrete makes extensive use of chemical admixtures, most commonly air-entraining, water-reducing, set-retarding and set-accelerating admixtures. Descriptions of many chemical admixtures can be found in Kosmatka and Wilson (2011).

Assessing the environmental impact of admixtures must include consideration of the impacts incurred in the production and transportation of the admixture to the concrete plant site. In general, the amount of admixture used is quite small. As a result, it is common for the environmental impact of chemical admixtures to not be included in an life-cycle assessment (LCA), although at least one study on concrete bridge decks has shown that admixtures can contribute a significant fraction of material production energy and emissions when heavily dosed (Keoleian et al. 2005).

Mixture Proportioning and Production

In designing more sustainable concrete mixtures, it is essential that the proper balance of workability, strength, volumetric stability, durability, and cost be struck. Trade-offs often exist when attempting to optimize any one or two of these criteria at the expense of another. For example, reductions in the water-cementitious materials ratio (*w/cm*) generally decrease paste permeability and increase paste density, thereby increasing both strength and durability; however, workability will likely suffer if other adjustments are not made at the same time, e.g., changes in aggregate gradation or the addition of chemical admixtures.

The concrete design, proportioning, and production processes must create a concrete paving mixture that economically meets all design strength, durability, and sustainability requirements over the pavement life cycle. Concrete with a lower cementitious materials content (e.g., 540 lbs/yd^3 [320 kg/m^3] or less), a high replacement (30 percent or greater) of portland cement with high-quality SCMs, durable aggregates, a properly entrained air-void system, and a relatively low *w/cm* (0.40 to 0.45 is considered good for most applications) will have a relatively low GHG emissions footprint at production and can be expected to have good long-term physical properties to provide excellent economic, environmental, and societal performance. However, there is no one "recipe" that will create "sustainable" paving concrete. Instead, the concrete technologist/producer needs to work within project constraints and the available materials to balance a number of discrete and competing variables to enhance concrete mixture sustainability.

Strategies for Improving Sustainability in Concrete Mixture Design

The major sustainability-related challenge facing concrete mixtures is that the production of portland cement is energy and GHG emission intensive. Reductions in those energy and emission levels are best achieved by expanding efforts to reduce the amount of portland cement used per yd^3 of paving concrete mixtures through improved aggregate gradations, the use of blended cements, and the increased use of SCMs added at the concrete plant. Other approaches for improving the sustainability of concrete materials, including the recycling of wash water in concrete production, increasing the use of RCWMs and marginal aggregates, and improving the durability of paving concrete, are summarized in table 1.

Other Concrete Mixtures and Emerging Technologies

There are other types of plant-mixed concrete that are sometimes used in paving applications with beneficial sustainability impacts. One of these is roller-compacted concrete (RCC), a stiff mixture of traditional concrete mixture components that is often proportioned with higher aggregate content and lower cementitious material content than conventional concrete, and is then placed and compacted in a manner similar to asphalt concrete. Another example is pervious concrete, comprising an open gradation of aggregate and lower cementitious material content, which allows precipitation to flow through voids in the mixture, thereby reducing storm water runoff and offering the potential to recharge groundwater supplies.

Table 1. Approaches for improving pavement sustainability with concrete materials production.

Concrete Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce Non-Renewable Energy Consumption and GHG Emissions in Cement Manufacturing	Improved cement plant efficiency through better energy harvesting and improved grinding	High capital cost but lower cost of manufacturing	Reduced energy consumption and GHG emissions	Less fuel consumed and emissions generated
	Utilization of renewable energy including wind and solar	High capital cost but lower cost of manufacturing	Reduced non-renewable energy consumption and GHG emissions	Less non-renewable fuel consumed and GHG generated
	Utilization of more efficient fossil fuels	Lowers manufacturing costs	Reduces emissions per unit of energy used	Cleaner burning fuel
	Utilization of waste fuels	Lowers manufacturing costs	Beneficial use of waste material	Reduces materials in landfills
	Utilization of biofuels	Reduces cost to cost neutral	Reduces GHG emissions	Reduces dependency on fossil fuels
	Minimize clinker content in portland cement through allowable limestone additions and inorganic processing additions	Reduces cost to cost neutral	Reduces GHG emissions and consumption on fuel	Reduces dependency on fossil fuels and lowers emissions
	Increase production of blended cements containing limestone or SCMs	Reduces cost	Significant reduction in energy consumption and GHG emissions. Redirects RCWMs from landfill	Reduces dependency on fossil fuels and less material sent to landfill
Reduce Energy Consumption and Emission in Concrete Production	Increase concrete mixing plant efficiency and reduce emissions	Increased capital cost but decrease production costs	Reduced emissions	Reduced local emissions including noise and particulate
	Utilization of renewable energy	Cost neutral to increase cost	Reduced emissions	Reduced emissions
	Use electrical energy from the grid	Depends on proximity to grid; should save cost	Reduced emission, better emission controls	Reduced local emissions
	Use less cement in concrete mixtures without compromising performance	Reduce cost of concrete	Reduced emissions and energy	Longer lasting pavements; less delays
	Use more blended cements without compromising performance	No impact on cost	Reduced emissions and energy	Longer lasting pavements; less delays
	Increase addition rate of SCMs at concrete plant without compromising performance	Reduce cost of concrete	Reduced emissions and energy	Longer lasting pavements; less delays
Reduce Water Use in Concrete Production	Recycle washout water	Cost neutral to slightly added cost	Use less water resources	Improved water quality
	Recycle water used to process aggregates	Cost neutral to slightly added cost	Use less water resources	Improved water quality
Increase Use of RCWMS and Marginal Materials as Aggregate in Concrete	Change specifications to allow greater amounts of RCWMs to be used in concrete without compromising performance	Reduced cost	Less landfill material, less transportation	
	Use RCWMs and marginal aggregates in lower lift of two-lift pavement	Cost neutral to slightly added initial cost; potential for reduced life cycle costs	Less landfill material, less transportation	
Improve the Durability of Concrete	Lower w/cm through admixture use	Cost neutral to slightly added cost	Longer lasting pavements	Less delays over life cycle
	Utilize an effective QA program throughout material production phase	Slightly added initial cost; save cost on litigations	Longer lasting pavements	Less delays over life cycle

Important emerging technologies in concrete materials include the development of high-volume SCM/portland limestone cement mixtures, which are becoming more common and offer the potential to significantly lower the GHG emissions associated with paving concrete. Another innovation is the development of photocatalytic cements that offer the opportunity to create highly reflective surfaces (with higher albedo and reduced lighting requirements) that remain clean while treating certain air pollutants through a photocatalytic reaction involving nanoparticles of titanium dioxide. Finally, lower carbon cementitious systems are becoming available, including calcium-sulfoaluminate and calcium-aluminate cements, geopolymers, and alkali-activated fly ash (Van Dam 2010).

SUSTAINABLE STRATEGIES IN CONCRETE PAVEMENT DESIGN

Concrete pavement design for a new or rehabilitation construction project is the process of:

1. Identifying the functional and structural requirements of the concrete pavement, including the sustainability goals.
2. Gathering key design inputs, such as material properties, traffic loadings, and climatic factors.
3. Selecting the concrete pavement type and associated materials, layer placement and thicknesses, geometric features, and construction specifications to achieve the desired performance.
4. Considering design alternatives based on the above to determine the preferred solution in terms of life-cycle cost, environmental impacts, and societal needs.

The identification of sustainability goals should be considered the first step in the process described above and shown below in figure 2. Although sustainability and life-cycle assessment are growing in importance, most highway agencies still primarily consider agency costs (either the lowest initial cost or the lowest life-cycle cost) in the pavement design process (GAO 2013). However, pavement designs that improve environmental sustainability can often also reduce life-cycle costs, largely as the result of reductions in natural resource requirements and energy consumption over the life cycle.

The following items may be included in project-specific requirements for the design of a particular concrete pavement: expected design life; smoothness; speed of construction; surface texture for friction, noise and splash/spray; storm water runoff; traffic delay associated with future maintenance; reliability considering cost and level of interruption of service for maintenance and future rehabilitation; ability to accommodate utility installation and maintenance; potential for future obsolescence (i.e., pavement will need to be replaced or removed before its design life is reached); urban heat island impact; and aesthetics.

Each of these considerations can have an impact on the sustainability of the pavement, but their relative importance will depend on the context of the design as well as the overall sustainability goals of the owner/agency and the specific project objectives. Each requirement should be assessed by the designer based on how the pavement will interact over its entire life cycle with users (e.g., passenger mobility and safety) and freight (i.e., ability to facilitate the transport of goods without damage or delay), the surrounding community, and the environment (local and global effects). The requirements of the users and community will also depend on the functional class of the roadway, and may also vary with time.

Some considerations and general guidance regarding the inclusion of sustainability as part of concrete pavement design include the following:

- Surface and structural performance.
  - Smoothness, texture and structural response affect vehicle fuel consumption. Smoothness also affects vehicle life and freight damage costs. These characteristics of the surface and structure vary with time and should be considered over the entire life cycle.
  - It is important to consider the impacts of future maintenance and rehabilitation activities on pavement sustainability, especially in terms of their effects on structural performance and pavement smoothness.
  - Surface performance is context sensitive in that it is very critical to pavements exposed to higher traffic volumes and less important from a fuel use standpoint to pavements carrying lower traffic volumes. For pavements carrying heavy traffic volumes, the environmental benefits of keeping the pavement smoother can far outweigh the negative environmental impacts of materials production and construction associated with intervening maintenance or rehabilitation.

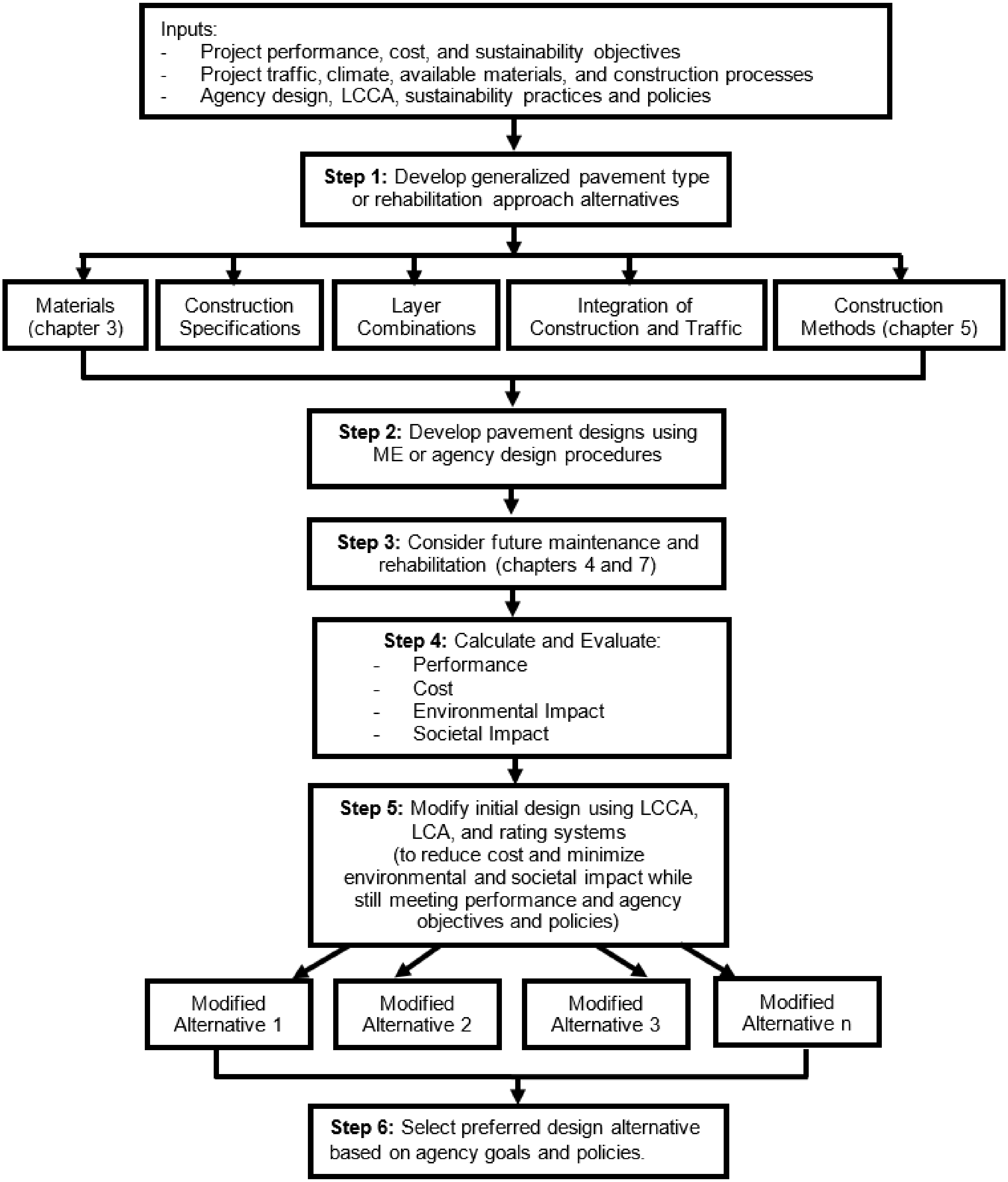


Figure 2. Overall process for considering sustainability in pavement design.
(Note: Chapter numbers refer to the chapter in FHWA-HIF-15-002 [FHWA 2015]).

- Design life selection.
  - The functional and structural pavement life is influenced by traffic and environmental factors.
  - The selection of the design life should include the consideration of higher initial economic costs and environmental impacts associated with longer life designs versus higher future costs and environmental impacts associated with shorter life designs because of the need for additional maintenance and rehabilitation activities.
  - The selection of the design life should include consideration of end-of-life alternatives or use of extremely long-lived pavement which will not be expected to need reconstruction.
- Concrete pavement type selection.
  - The concrete pavement type selection impacts every phase of the pavement life cycle, including the selection of initial materials and construction as well as the future maintenance and rehabilitation, use phase, and end of life (if not designing extremely long-lived pavement).
  - The relative sustainability impacts of different concrete pavement types depend on location, design traffic, and available materials.
- Construction and materials selection.
  - The impacts of materials selection on sustainability depend on the local sources of materials and the transportation alternatives available.
  - The ability to achieve quality construction with available materials and construction equipment and expertise impacts the pavement sustainability.
  - Traffic delays in construction work zones may result in negative sustainability impacts where traffic volumes are high and traffic management plans (TMP) cannot mitigate delays. Safety is also affected by the type and duration of construction work zones.
- Construction quality requirements.
- Recycling strategies.

The impact on pavement environmental impacts of these types of decisions can be assessed through use of LCA and overall sustainability can be assessed through use of sustainability ratings systems as part of an overall assessment process.

Mechanistic-Empirical Design

Mechanistic-empirical (ME) pavement design methods offer much greater opportunity than empirical design methods to consider alternative materials, pavement structures, and construction procedures, including comparisons of alternatives offering improved cost and environmental sustainability. Empirical pavement design methods, which are based on observations of the performance of in-service pavements without consideration of the mechanics of pavement behavior, can only consider how pavements perform within the range of conditions (e.g., material types, pavement types and design features, environmental conditions and traffic loadings) upon which the design model was calibrated. ME design directly considers key material properties and geometric conditions (e.g., layer stiffness and strength, thermal properties, fatigue resistance, slab size, and joint support) and how the pavement reacts to applied vehicle and environmental loads and is able to relate those parameters directly to pavement performance through available response and performance models. Thus, ME design allows the development of designs using new materials, geometries, and other conditions that have not been used or encountered before based on the results of analyses conducted using pavement structural models.

ME design can estimate critical concrete pavement distresses (e.g., slab cracking, faulting, joint spalling and punchouts) and roughness (i.e., International Roughness Index [IRI]) versus time, which allows the designer to consider alternative trigger levels for maintenance and rehabilitation. In addition to changes in materials and pavement types, ME design permits the evaluation of changing construction specifications through consideration of their effect on materials properties.

The AASHTOWare Pavement ME Design Software is currently the most commonly used ME tool for pavement design (both for new pavements and overlays) with some state DOTs (e.g., Minnesota, Texas, and Illinois), industry organizations, and countries utilizing other concrete pavement ME design procedures and software tools. ME design methods are available for both new concrete pavements and for rehabilitation design. Structural rehabilitation strategies for concrete-surfaced pavements include concrete (bonded and unbonded) and asphalt overlays as well as reconstruction.

Pavement Design Strategies for Longevity

Longer life design options may afford the opportunity to reduce life-cycle costs, user delays, and environmental impacts as compared to a standard 20-year pavement design. Longer life pavements with design lives of 30 to 60 years (or more) can be achieved as a policy objective in new, rehabilitated, and reconstructed pavements and are generally justified for higher volume facilities.

Longer life pavements use more durable materials and/or provide greater structural capacity. Higher structural capacity can be achieved by increasing pavement thickness, by increasing the stiffness and/or strength of critical layers, or both. Because of the increased thicknesses or increased material stiffnesses/strengths, or the use of more durable materials, longer life designs may have higher initial costs and/or greater initial environmental impacts, but the overall life-cycle costs and environmental impacts are often expected to be less.

Longer life concrete pavements are designed to resist the heavy truck traffic that will cause repeated load distresses such as fatigue cracking, faulting, and punchouts, requiring only periodic retexturing of the surface to restore smoothness, friction, and noise performance. These design objectives are achieved by using durable concrete mixtures, adopting slightly thicker concrete slabs placed on non-erodible bases, using properly designed and corrosion-resistant dowel bars or reinforcing steel, and incorporating stress-relieving design features, such as tied concrete shoulders or wide slabs. Figure 3 shows an example of a longer life CRCP designed for improved fatigue resistance and low maintenance requirements.

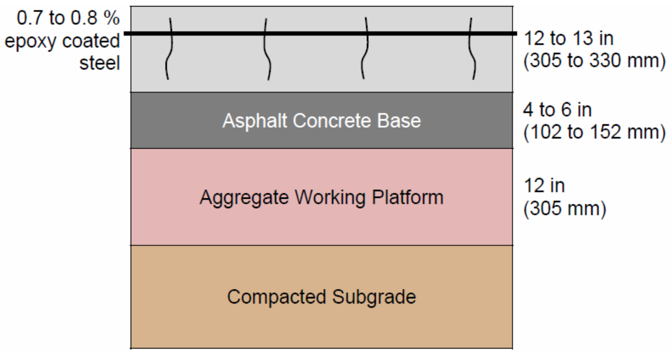


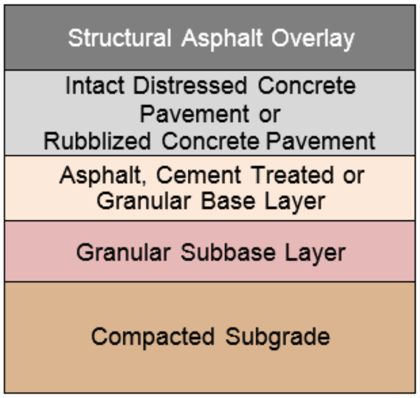
Figure 3. Example of longer life CRCP design.

It is noted that poor drainage conditions can contribute to early failures and reduced pavement life, and therefore can significantly increase the environmental and cost impacts of the original pavement because of early and more frequent maintenance and rehabilitation activities. It is essential that the need for drainage be reviewed for all new and rehabilitation projects.

Concrete Pavement Rehabilitation Using Overlays

Rehabilitation strategies for concrete surfaced pavements include structural bonded and unbonded concrete overlays and structural asphalt overlays, as shown in Figure 4. The use of concrete overlays reduces construction time and environmental impact when compared to reconstruction while extending the performance life of the pavement section. They can be designed to provide intermediate or long-life sustainable pavement design alternatives.

Structural Asphalt Concrete Overlay



Structural (Bonded/Unbonded) Concrete Overlay

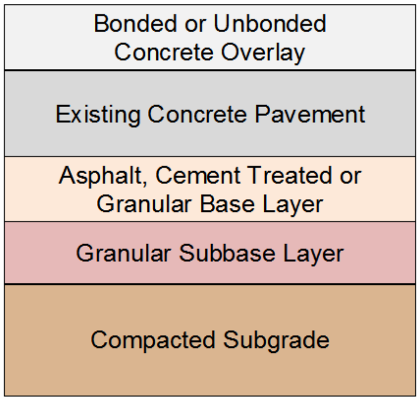


Figure 4. Cross section of concrete pavement structures rehabilitated with overlays (not to scale).

Concrete overlays of existing concrete, asphalt, or composite (asphalt over concrete) pavements are either unbonded or bonded (Harrington 2008; Harrington and Fick 2014; Torres et al. 2012). Unbonded concrete overlays are used when the existing pavement deterioration is so advanced that it cannot be effectively corrected prior to overlaying. An unbonded concrete overlay is typically constructed 6 to 12 inches (150 to 300 mm) thick. When placed on an existing concrete pavement, it utilizes a separation layer between the existing concrete and the new concrete overlay (Smith, Yu, and Peshkin 2002). This has traditionally been a 1 to 2-inch (25 to 50-mm) thick layer of asphalt material, although some agencies are now using non-woven geotextile materials as a separator layer (Harrington and Fick 2014). This separation layer is placed to ensure independent behavior of the overlay and underlying slabs, thereby minimizing the potential for reflection cracking.

Bonded concrete overlays consist of a thin layer of concrete (typically 3 to 4-inches [75 to 100-mm] thick) that is bonded to the existing concrete pavement (Smith, Yu, and Peshkin 2002). These are used to increase pavement structural capacity, extend pavement life, or to improve the ride quality of an existing pavement that is in relatively good condition. A critical construction and performance aspect of bonded concrete overlays is the achievement of an effective bond between the overlay and the existing pavement in order to create a monolithic pavement system. Details concerning bonded overlay design details can be found in Harrington (2008) and Harrington and Fick (2014).

For structural asphalt overlays of concrete pavements, the overlay is typically placed directly on the existing concrete pavement using a tack coat. The existing concrete pavement may be broken into smaller sized pieces using slab-fracturing techniques, such as crack and seat or rubblization, as a means of slowing or minimizing the development of reflection cracking (Thompson 1989; NAPA 1994; Hoerner et al. 2001; TRB 2006). When the concrete pavement is in poor condition with extensive patches or materials problems, rubblization will reduce the concrete to a state similar to aggregate base. However, rubblization may not be appropriate if the subgrade is too soft to support the rubblizing process, or if the pavement does not exhibit distresses for which rubblizing is the best alternative (Heckel 2002).

Design with Local and Recycled Materials

Traditional concrete pavements sections include opportunities for the use of recycled materials in the base and subbase layers, as well as various recycled materials in the concrete layer. These options are often particularly attractive and decrease environmental impacts in reconstruction when the original pavement structure is the source of the recycled materials. The use of two-lift composite pavement, where the upper lift may include abrasion-resistant and more durable materials while the lower lift utilizes recycled materials or other local aggregates of less suitable for use in the concrete surface, offers another effective strategy for improving pavement sustainability. This optimized approach serves to not only lower costs, but also reduces environmental impacts as well, primarily by reducing the environmental burden of transporting materials.

Additional Design Strategies and Features that Impact Sustainability

Surface Texture

Many different textures are available for concrete pavement surfaces, and each offers different potential noise and friction characteristics, which impact environmental and societal aspects of pavement sustainability. While the selection of a concrete pavement surface texture can be considered to be a part of the design process, the successful implementation of that texture and its impacts on pavement sustainability are highly dependent on construction techniques. The impacts of constructed pavement characteristics are addressed later in this document.

Storm Water Management

Pavements can be constructed using permeable (also called "pervious") materials to capture and store storm water runoff, allowing it to percolate into the ground and thereby recharge groundwater supplies and/or control discharge outflow. Fully permeable pavements are defined as those in which all pavement layers are intended to be permeable and the underlying pavement structure serves as a reservoir to store water during precipitation events in order to minimize the adverse effects of storm water runoff. Examples of fully pervious concrete pavement structures are shown in figure 5. An FHWA tech brief on fully porous pavements outlines an overview of pervious concrete and its use in pavement applications (FHWA 2012).

The U.S. EPA (2010) cites the use of fully pervious pavements as a Best Management Practice (BMP) for handling storm water runoff on a local and regional basis. Most applications of fully porous pavements in North America have not been subjected to high-speed traffic or heavy trucks, which reflects concerns about durability. Structural design methods are empirical in nature and are available from the American Concrete Pavement

Association, including design software. For state highway agencies, fully permeable pavements are being considered as a shoulder retrofit adjacent to conventional impermeable pavement with geosynthetics used to prevent water from affecting the layers in the impermeable pavement, and for some low-speed applications carrying trucks. An ME design

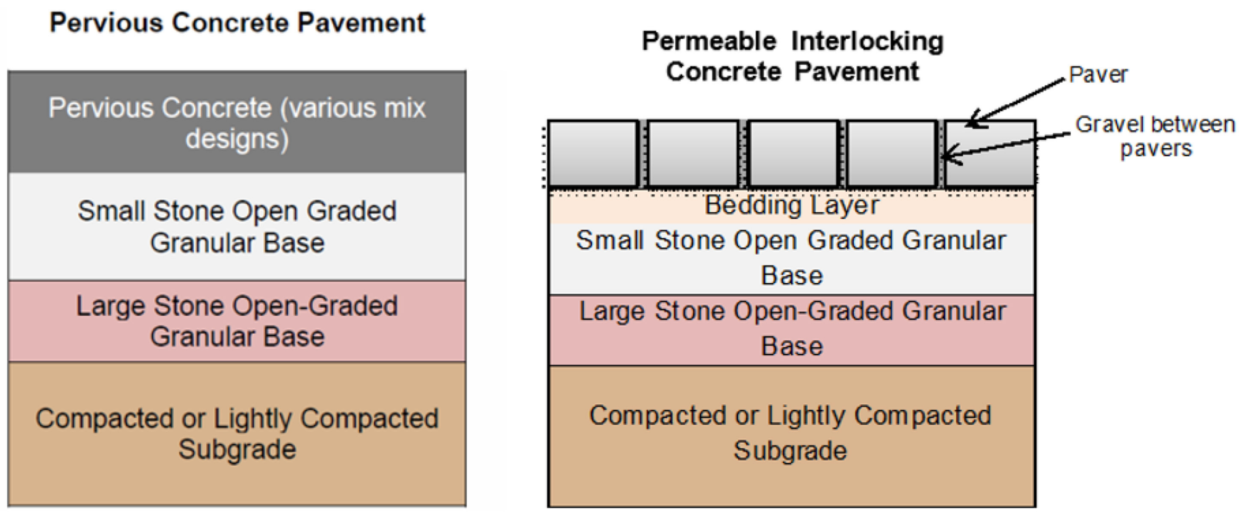


Figure 5. Examples of fully permeable concrete pavement systems.

approach and a preliminary life-cycle cost analysis (LCCA) have been produced for two types of fully pervious concrete pavements to potentially carry trucks (considering both structural and hydraulic capacity) for California conditions (Jones et al. 2010; Li, Jones, and Harvey 2012a; Li, Jones, and Harvey 2012b). An ME design approach for fully permeable interlocking concrete pavement validated with accelerated pavement testing is available from the Interlocking Concrete Paving Institute.

Modular Pavement Systems

Modular pavement systems are composed of precast components that can be used to rapidly construct or repair a section of roadway, thereby reducing user delays, or to provide an aesthetically pleasing design. Modular pavements can permit the use of thinner and longer lasting structures that could reduce environmental impacts over the pavement life cycle. One type of modular pavement is precast concrete slabs, which are typically used for very short construction windows to minimize user delays and to provide better performance than might be obtained using cast-in-place construction. High quality and durability is possible with precast concrete pavement systems because the concrete is cast and cured under controlled conditions and is not exposed to potentially damaging field conditions and traffic while curing. Another type of modular pavement system is interlocking concrete pavers, which is typically used on low-speed facilities or in urban areas to provide aesthetically pleasing roadways (ASCE 2010; Smith 2011). Some removable and reusable modular pavement systems also allow easy access for utility repairs, thereby reducing repair costs and minimizing user delays.

Issues and Trade-offs in Concrete Pavement Design

Consideration of Future Maintenance and Rehabilitation

The design of new pavements and rehabilitation projects should include consideration of future maintenance and rehabilitation that will be required based on the design decisions. These decisions should include consideration of maintaining the overall structural capacity of the pavement, its overall functional capabilities (e.g., smoothness, friction), and future roadway recycling and reuse.

Consideration of Use Phase in Design

The main design factors that have the most significant effects on pavement sustainability in the use phase are:

- Smoothness over the design life of the pavement (increased pavement roughness increases vehicle fuel consumption and may reduce time between maintenance and rehabilitation activities).
- Overall pavement longevity (increased longevity decreases life-cycle costs and reduces the environmental and social impacts associated with materials production, construction, and periodic maintenance and rehabilitation).

The relative importance of each of these factors depends, in large part, on the traffic volumes using the facility. Where traffic volumes are heavy, the benefits of smoothness over the design life can be much larger than material production and construction impacts. Conversely, for low-volume roads and highways, material production and construction will often tend to dominate the net calculation of environmental impacts over the life cycle.

Consideration of Early versus Later Impacts

One approach to assess the risk of whether life-cycle cost, user delay and environmental impact goals are met in design is the concept of "payback time." Payback time is defined as the period between the initial impact of an alternative with higher initial impact due to use of premium materials and/or thicker layers and the time to achieve a zero difference compared to the standard approach, after which there is a net reduction in impact. Simply put, it is the time required to recoup the benefits (e.g., cost, environmental, or social) associated with a pavement design investment. For pavement, this involves increasing the time (years) before the first rehabilitation or reconstruction, reducing the level and frequency of maintenance during the life, and keeping a pavement smoother over its life.

A payback analysis provides an indication of the uncertainty of achieving a reduction in environmental impact over the life cycle due to a design decision, with longer payback times having greater uncertainty regarding the ability of the assessment to accurately quantify them and whether they will actually occur. Using appropriate tools and methods like LCCA and LCA, payback time can be calculated to evaluate when the initial investment made for longer life pavements can be regained from economic and environmental perspective.

An example of the payback time for a specific case study is provided in figure 6, which shows a comparison of the GWP of the materials production and construction phases for pavements with 20-, 40- and 100-year design lives (all using the same materials). It can be seen that the 40-year pavement initially has more GWP than the 20-year pavement, primarily due to a thicker structure, but that the difference is made up after 29 years; furthermore, over a 100-year analysis period the 40-year pavement has approximately half the GWP of the 20-year pavement.

The example shown in figure 6 only considers the impacts of material production and construction, and consideration of use phase impacts will likely change the cross-over point. Approaches for considering the time dependency of impacts in LCA and carbon footprints are being developed (Kendall 2012).

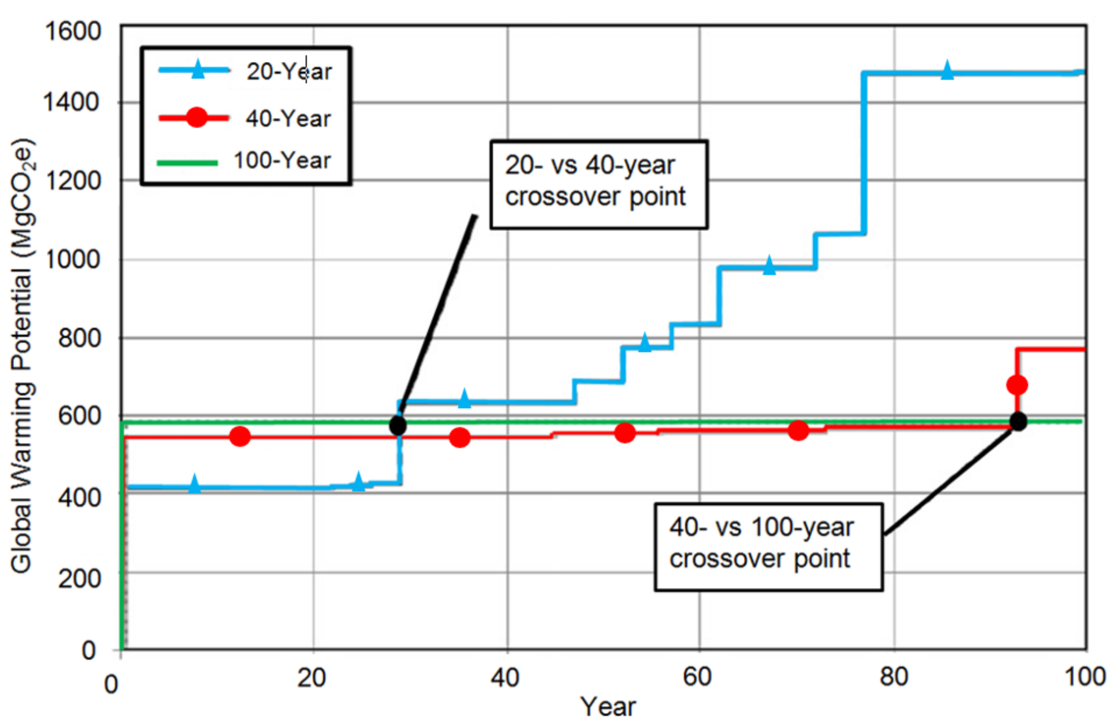


Figure 6. Example of payback time analysis considering only the material production and construction phases of three different pavement design lives (modified from Santero 2009).

SUSTAINABLE STRATEGIES IN CONCRETE PAVEMENT CONSTRUCTION

Critical areas of pavement construction that can have a significant effect on the overall sustainability of a paving project include: (1) fuel consumption during material transport and construction operations; (2) exhaust and particulate emissions; (3) traffic delays, congestion, and noise emissions generated during construction; (4) construction quality, as it impacts pavement performance and overall life; and (5) constructed characteristics of the pavement surface, which impact surface friction (safety), noise, and possibly fuel efficiency during the use phase. These areas can be categorized as being related to construction operations (areas 1, 2 and 3) or constructed characteristics, including quality (e.g., areas 4 and 5). Some of these critical construction items that can positively affect pavement sustainability are discussed in the next sections.

Sustainability of Pavement Construction Operations

Pavement construction factors that impact pavement system sustainability over the life cycle include: (1) construction-related energy consumption; (2) effects of construction operations on the surrounding area (including particulate and gas emissions, noise, effects on residents and businesses, and effects on wetlands and streams); and (3) the economics of construction practices, including user costs resulting from construction-related traffic delays.

Construction-Related Energy Consumption

In general, pavement construction is an energy-intensive process that involves excavation, earthwork movement, material processing, production and placement, and compaction/consolidation of the paving layers. The associated energy consumption of equipment is a function of the equipment/vehicle operation energy efficiency, which in turn is a function of the operation of that equipment within ideal power bands and minimization of idle time and engine speed during idle time. Other factors that can affect energy consumption include fuel types used (e.g., diesel fuel, gasoline, biodiesel and compressed natural gas) and the type of power source for stationary construction equipment (i.e., generator driven vs. grid powered). External factors that influence construction fuel consumption (independent of equipment efficiency) include site operations (e.g., haul distances, construction staging, and the need for multi-pass operations) and specific site-related conditions (e.g., quality and maintenance of haul road surfaces).

Effects on the Surrounding Area

The use of heavy equipment for earth moving and construction operations generates engine combustion emissions that may significantly impact local air quality in surrounding areas. Heavy-duty construction equipment is usually diesel powered, which produces NO_x, GHG, and diesel particulate matter (PM) as significant emissions. Diesel exhaust PM emissions are reported as a toxic air contaminant, posing chronic and carcinogenic public health risks (AEP 2012). The EPA has established stringent standards for carbon monoxide, volatile organic carbon, nitrogen oxides, and PM that a vehicle and engine may emit, and manufacturers, refineries, and mixing plants are responsible for meeting those standards.

Construction processes can also indirectly impact the surrounding area through resulting congestion, traffic delays, noise and other adverse effects. Construction analysis programs for pavements, such as CA4PRS (Lee, Harvey, and Samadian 2005), can be used to analyze the effects of pavement design, construction logistics, and traffic operation options on construction-related traffic delays and construction window policies. The impact of traffic delays on vehicle energy consumption and GHG emissions relative to the impacts of materials production, construction, and the use phase will depend on the types of delay and the number and types of vehicles affected.

Economics of Construction Practices

The construction practices used have direct bearing on both the initial construction costs and the long-term, life-cycle costs of the pavement project. Changes in construction practices to enhance the sustainability of the project (such as noise and pollution reduction procedures, controlling erosion and storm water runoff, and providing better local access) are expected to incur increased costs, which must be considered and weighed against expected benefits over the life cycle of the pavement to determine their effective impacts. Changes that incur unacceptable economic expense may not be easily adopted, in spite of potential environmental or societal benefits.

In addition, construction work often results in reductions in roadway capacity because of geometric restrictions, reduced speed limits, temporary closures, detours, and other congestion-inducing activities. Significant costs are associated with construction-related traffic delays and congestion, including lost time and decreased productivity for users, wasted fuel, and economic loss due to the inefficient movement of goods and services. Highway construction work zones account for nearly 24 percent of nonrecurring congestion in the U.S. (other sources include vehicle crashes and breakdowns, and weather conditions), which translates to 482 million vehicle hours of delay per year (USDOT 2006). Highway construction work zones are estimated to be responsible for 10 percent of all highway congestion in the U.S., which translates to an annual fuel loss of $700 million (Antonucci et al. 2005).

Techniques for Improving the Sustainability of Construction Operations

The following sections describe strategies for improving the sustainability of construction operations. A national effort is currently underway to develop a guidebook for selecting and implementing sustainable highway construction practices under NCHRP Project 10-91.

Reducing Construction-Related Energy Consumption and Emissions

Some practices for reducing fuel consumption and emissions from construction equipment include minimizing haul distances with the use of on-site recycling and optimally located staging areas (Ferrebee 2014; Smith et al. 2014), selecting appropriate equipment types and sizes for the job, implementing limitations on idling, using alternative fuels, retrofitting construction equipment with improved emissions control equipment, and using hybrid equipment.

Reducing Construction Impacts on Surrounding Environment

There are a number of practices that can be adopted to improve air quality issues associated with pavement construction other than those that result from vehicle emissions. Some of these strategies include water sprinkling and other dust control techniques, regular maintenance of dust collectors at asphalt and concrete plants, and consideration of the proximity of residential and light commercial areas in the selection of plant and materials storage locations.

Approaches to reducing noise and noise impacts include equipment modifications and proper equipment maintenance, and time-of-day restrictions on some (or all) construction activities. Practices for minimizing pollution from runoff and erosion include the use of perimeter control barriers (fences, straw bales, etc.), minimization of the extent of disturbed areas, application of erosion control matting or blankets, and site planning to store/stockpile materials away from waterways.

Traffic delays and disruption of residents and businesses can be reduced by the use of effective traffic control and lane closure strategies, the establishment of performance goals and measures for work zones, the use of project management software to optimize construction sequencing, and the use of intelligent transportation systems to dynamically manage traffic.

Accelerated construction techniques can also be employed to minimize the duration of construction and associated lane closure times. Examples of materials and construction processes that may accelerate construction include the use of materials such as rapid-setting or high-early-strength concrete, RCC, modular concrete, and rubblization followed by asphalt overlay. Each of these options may expedite the construction process, thus reducing user delays, reducing emissions, and improving safety (reduced risk of crashes).

Concrete haul trucks and other equipment must be washed out frequently, but concrete wash water is toxic to fish and other aquatic life and can contaminate drinking water supplies if not handled appropriately. In addition, washout sediment can clog pavement drainage systems. Therefore, concrete wash water must be prevented from entering waterways, drainage systems, and groundwater. Best management practices include the return of all concrete waste and wash water with each concrete truck for disposal at the concrete batch plant. Guidelines for using increasing amounts of "grey water" (from washing concrete production equipment and trucks) in concrete mixtures are rapidly becoming more common and accepted. At a minimum, an on-site concrete washout area should be established to collect washout water.

Impacts of Constructed Characteristics on Pavement Sustainability

The sustainability of a pavement structure can be improved through increases in pavement performance (e.g., longer service life, higher and maintained levels of smoothness and frictional properties, etc.), as described herein.

Construction Quality

Long service life is one of the primary drivers of pavement sustainability and the ability to achieve that long service life is strongly impacted by the quality of construction. In fact, the potential gains in sustainability afforded by the optimization of structural design, the use of highly durable or recycled materials, and the improved efficiencies in the production of cement and other materials can be completely negated by poor construction quality and improper construction techniques.

In many cases, increases in performance can be achieved with small increases in construction quality and concomitant reductions in overall variability. A careful review of construction specifications may show where increased levels of quality could be achieved that would positively impact performance. The implementation of effective quality assurance (QA) plans will promote higher levels of quality.

There are many aspects of concrete pavement construction for which QA is essential in order to achieve the full potential for longevity (and, therefore, sustainability) of concrete pavements. These include (but are not limited to): string line setup and maintenance (for control of pavement thickness and initial ride quality); plant certification; proper equipment setup and hauling (including haul time restrictions in normal and hot weather); proper placement, installation, and (where applicable) alignment of dowel bars, tie bars, and slab reinforcement; proper placement of the concrete (to minimize segregation and maintain a constant head of material in front of the paver); control of water use at the job site; proper materials QA (e.g., monitoring mixture consistency through air, slump and unit weight testing, as well as thickness control and strength or maturity testing); proper concrete consolidation without over-vibration (through the use of vibratory frequency monitors and their adjustment with variations in the concrete mixture); proper selection and use of curing materials; and accurate joint marking (to ensure proper panel size and dowel embedment lengths) and sawing operations. Best practices for all these aspects of concrete paving are described in detail in several key references (ACPA 2008; ACPA 2010).

Smoothness is an important pavement construction quality indicator. Achieving a high level of smoothness during initial construction as well as maintaining it throughout the service life of pavements is considered to be a key factor in improving overall fuel economy and reducing vehicle related emissions, especially for heavily trafficked sections. For pavements carrying high traffic volumes, the effects of pavement smoothness on fuel economy and resulting impacts on energy use and GHG emissions can be greater than any differences caused by different materials or construction techniques. An example of this can be seen in figure 7 (Wang et al. 2012), which shows the time it takes to pay back the initial energy and emissions caused by three percent slab replacement followed by diamond grinding of all lanes (construction and materials shown as negative value at beginning of life) through vehicle fuel savings after construction, compared with leaving the pavement with a rough surface. While this is only one example, the figure illustrates the effects of three values of constructed smoothness, with lower levels of constructed smoothness resulting in lower net savings in energy and emissions compared to high levels of construction smoothness.

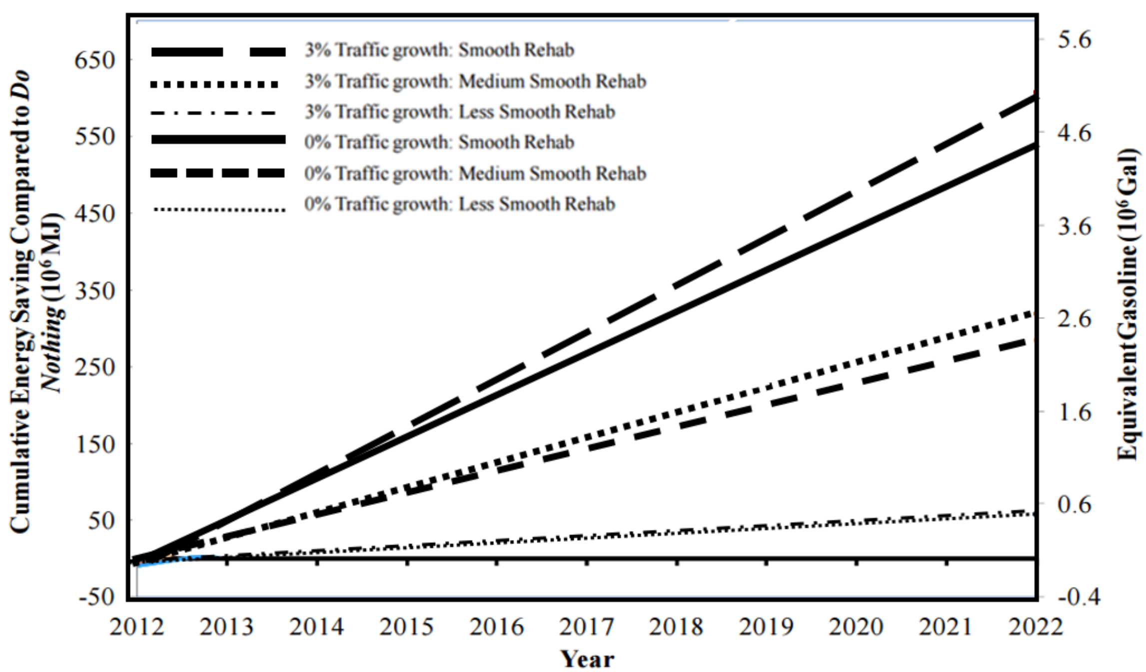


Figure 7. Payback time in MJ and equivalent gallons of gasoline for a high volume interstate route over 10-year analysis period for three percent slab replacement and diamond grinding of all lanes versus leaving the pavement rough, considering three levels of constructed smoothness (Wang et al. 2012).

(Initial IRI values: less smooth construction = 152 to 176 inches/mile depending on lane [2.4 to 2.8 m/km], medium smooth construction = 116 to 140 inches/mile [1.8 to 2.2 m/km], smooth construction = 80 to 103 inches/mile [1.3 to 1.6 m/km]).

Studies have also shown that, when structural or material durability problems are not present, improvements in initial ride quality translate directly into longer pavement service life (Smith et al. 1997). Obtaining good initial smoothness levels during the construction of new or rehabilitated high traffic volume roadways, and maintaining those levels of smoothness throughout their service lives, can result in large reductions of use-phase energy consumption and emissions compared to the impacts associated with the use of different materials or construction techniques. Smoothness acceptance levels should be part of the construction specifications.

Strategies for Improving Concrete Pavement Construction Quality

Performance specifications are generally accepted as a way to improve the quality of construction and also to encourage contractors to develop innovative solutions that save time, minimize traffic delays, and enhance durability. SHRP2 project R07 undertook the development of such performance specifications and the project report discusses the implementation of performance specifications in the context of various contract delivery methods including design-build, design-bid-build, and other innovative contracting variations (Scott et al. 2014).

The construction of two-lift concrete pavement structures generally results in better initial pavement smoothness, which can extend pavement maintenance cycle times and service life. Two-lift paving also facilitates a more sustainable use of different types of materials in the various paving layers. However, single-lift construction offers clear benefits in terms of reducing the number of paving passes and requiring the operation of fewer pieces of construction equipment for a given project, i.e., two paving machines and two batch plants are often employed for two-lift concrete paving versus one of each for single-lift paving.

There are many other techniques and strategies for improving the quality of concrete pavement construction, including the development and implementation of appropriate construction quality control protocols, preconstruction meetings/training (for both inspection and contractor personnel), the use of incentives for materials and constructed pavement characteristics that are associated with improved pavement durability and longevity (e.g., lower initial IRI, the use of superior quality aggregates, reduced water-to-cementitious material ratio, etc.), the use of modern paving equipment and techniques, and more.

Finishing and Texturing

Concrete pavement finishing and texturing affect pavement sustainability through their potential impacts on service life (which impacts maintenance activities and life-cycle costs) and initial smoothness (which affects user costs, such as vehicle fuel efficiency and wear and tear).

Over-finishing and the use of water as a surface finishing aid must be avoided because loss of surface durability may result. Manual efforts to remedy minor surface defects can result in improved appearances at the cost of pavement ride quality. If good mixture proportioning, hauling, and placement practices are followed and if the paving equipment is properly set up and well maintained, hand finishing should be performed sparingly and only as necessary to correct significant pavement surface flaws and profile defects. ACPA (2010) provides additional details concerning best practices for concrete pavement finishing.

Concrete pavement surface texture must be constructed to provide both adequate surface friction (sustainability through safety and reduced crash rates, particularly in wet weather) while also minimizing the generation of noise through tire-pavement interaction. There are many concrete pavement surface texture options, including transversely oriented textures (e.g., transverse tining, brooming and grooving), longitudinal textures (e.g., longitudinal tining, brooming, grooving, turf drag, diamond grinding and Next-Generation Concrete Surface [NGCS]), and textures with no particular orientation (e.g., porous concrete, and exposed aggregate finishes). Details concerning the tire-pavement noise and friction characteristics of each of these surface types throughout the use phase of the pavement life cycle are presented in chapter 6 of Van Dam et al. (2015), ACPA (2006), and Henry (2000). The successful use of some of these types of texture require specific mixture design characteristics (e.g., the inclusion of siliceous fine aggregate for microtexture, specifically graded and shaped coarse aggregate particles for exposed aggregate finishes, and low water-cementitious ratios for durable turf drag finishes) and construction techniques to achieve proper texture depth and pattern spacing.

Sustainable Concrete Pavement Construction Summary

Concrete pavement construction activities offer many opportunities to adopt practices that improve the sustainability of the pavement system. Highly visible examples include the use of on-site recycling to produce pavement foundation layers and the protection of groundwater and local fauna by collecting and removing (for recycling) concrete wash water. Less obvious examples are the impacts that good construction practices can have on fuel consumption, user vehicle expenses, and agency repair costs during the use phase.

The potential impacts of the concrete pavement construction phase (i.e., construction equipment and activities) on overall life-cycle assessment for a given roadway may be relatively small, particularly when compared to the impact of the materials phase and the use phase (Santero and Horvath 2009; Ferrebee 2014). Zapata and Gambatese (2005) indicate that the "placement phase" consumes only about 3 percent of the total energy in the pavement life cycle. However, the construction phase is a phase over which engineers and contractors have a great deal of influence. Therefore, it is important to be cognizant of the many ways that construction phase activities can influence overall pavement sustainability.

SUSTAINABLE STRATEGIES FOR THE PRESERVATION/MAINTENANCE OF CONCRETE PAVEMENTS

Diminishing budgets and recognition of the benefits of considering life-cycle costs have motivated changes in agency policies that advocate financial and environmental sustainability through the practice of pavement preservation. Pavement preservation inherently improves pavement sustainability. It often employs low-cost, low-environmental-impact treatments to prolong the life of the pavement by delaying major rehabilitation activities. This conserves energy and virgin materials while reducing GHG emissions over the life cycle. Furthermore, well-maintained pavements provide smoother, safer, and quieter riding surfaces over a significant portion of their lives, resulting in higher vehicle fuel efficiencies, reduced crash rates, and lower noise impacts on surrounding communities, which positively contributes to their overall sustainability.

Pavement preservation is primarily concerned with minimizing the project-level, life-cycle cost of the agency. To minimize the agency life-cycle cost, only the materials and construction phases of the pavement life cycle are considered, since use-phase costs (primarily vehicle operating costs) are mostly borne by pavement users and not by the agency. For low-volume roads, where the environmental impact of vehicle operations is small, improvements in the agency life-cycle cost and improvements in sustainability are generally compatible, since the objective for both is to minimize the frequency of treatment applications and the amount of material used for each treatment. Therefore, for low-volume routes, the general strategy for improving sustainability is to minimize the amount of materials used and the number of construction cycles over the life cycle by optimizing the treatment selection and timing to avoid major structural damage while minimizing costs.

For higher traffic volume roadways, the environmental impact of the use phase becomes increasingly important, often to the point that, for very high-volume routes, the materials and construction phase impacts of maintenance and preservation become very small relative to the influence of pavement smoothness, macrotexture, and stiffness on vehicle operations (primarily in terms of fuel economy). Depending on the route, the optimization of the environmental benefit will require balancing the impacts incurred to keep the pavement in good condition (in order to reduce vehicle operating costs) with the impacts resulting from materials production and construction of the treatment. The optimization of environmental benefits for high-volume routes is, therefore, much more complex than it is for low-volume routes because it may increase agency economic life-cycle cost as the need for more frequent treatment is increased to maintain conditions that reduce road user costs and vehicle-produced emissions.

Overview of Concrete Pavement Preservation and Maintenance Techniques and their Impacts on Sustainability

The following maintenance and preservation treatments are most commonly considered for concrete pavements: joint/crack sealing; slab stabilization/slab jacking; partial-depth repairs; full-depth repairs; dowel bar retrofit; slot/cross stitching; retrofitted edge drains; diamond grinding/grooving; and nonstructural surface treatments or overlays (both concrete and asphalt) designed to enhance functionality (e.g., thin wearing courses for friction and/or noise). Various resources are available that discuss concrete pavement preservation/maintenance strategies as well as each treatment type, including the types of pavement conditions addressed, how each treatment should be constructed, and their cost effectiveness.

Key parameters affecting sustainability of concrete pavements in selection of a preservation or maintenance technique are timing of treatment, service life of the individual treatment, smoothness performance after treatment is applied, duration of lane closures, and life extension added to the existing pavement. While there is abundant literature available on the topics of how pavement materials, design, and construction influence sustainability, far less information is available on how pavement maintenance and preservation treatments and practices impact sustainability. Table 2 provides a qualitative summary of the impacts of several concrete pavement preservation and maintenance treatments on

Table 2. Summary of relative sustainability impacts of selected concrete-surface pavement preservation and maintenance techniques.

Treatment	Treatment Life (✓to ✓✓✓✓)	Initial Cost ($ to $$$$)	Environmental Impact	Societal Impact
Joint Resealing	✓	$	Low	Reduced traffic delays; less pleasing aesthetics and potential roughness.
Partial-Depth Repair	✓✓	$$$	Varies with material used and amount of repair required.	Significant potential improvement in ride quality; rapid-set materials can reduce construction-related traffic delays.
Full-Depth Repair	✓✓✓	$$$$	Medium to high (Varies with amount of patching, type of materials used, cast in place vs. precast).	Precast panels can reduce construction-related traffic delays. Potential aesthetic problems.
Dowel Bar Retrofit	✓✓✓✓	$$$	Variable Highly negative initial impact during construction; potential long-term, positive impact through life cycle	Improves ride quality by controlling faulting. Aesthetics can be negatively affected.
Diamond Grinding	✓✓✓	$$	Medium to high (Depends on how much surface is removed, etc.)	Improves friction (safety), reduces tire-pavement noise.
Grooving	✓✓✓	$$	Low	Improves wet-weather safety, reduces noise.
Bonded Concrete Overlay	✓✓✓✓	$$$	Medium Virgin aggregate and cement materials increase impact.	Potential for improved friction, drainage, ride quality, aesthetics, etc.
Ultra-Thin Asphalt Wearing Course, typically open graded with rubberized or polymerized binders	✓✓	$$$	Variable Depends on type of material used and life of treatment	Primarily used to enhance functional surface characteristics of the pavement, most notably noise reduction and improved friction

pavement sustainability. Although any given concrete-surfaced pavement treatment can be applied alone (e.g., full-depth patching can be used to repair a localized slab failure), it is far more common to use several treatments together in an approach often referred to as concrete pavement restoration (CPR) to restore a structurally sound but distressed concrete pavement to a higher level of serviceability. Thus the sustainability impact of any one treatment is very difficult to assess. Ultimately the economic, environmental, and social impacts of the entire strategy should be assessed in its entirety.

Construction quality plays a role in the sustainability impacts of pavement preservation and maintenance that is similar to the role played in new construction. Increased construction quality extends pavement and treatment life and reduces environmental burden, and treatments that are constructed with higher levels of initial smoothness and that are maintained in a smooth condition over their lives will result in reduced energy use and GHG emissions. The additional effort required to achieve additional quality is generally very low.

For a high volume route, the timing and performance of the selected treatment can play a significant role in determining sustainability impact. More frequent maintenance and rehabilitation will result in preservation of existing pavement in good condition, and generally will result in a smoother and safer surface for road users. The improved smoothness can help reduce vehicle fuel use, provided users don't drive faster, and vehicle damage and associated road user costs. On the other hand, more frequent maintenance and rehabilitation result in more frequent environmental impacts from materials production and construction, and also result in greater cost for the agency (compared with leaving the pavement in bad condition without restoring it; the cost of keeping a pavement in good condition goes down over the life cycle) In general, the results change considerably depending on the expected treatment performance, traffic levels, and emissions from materials, construction, and end-of-life scenarios. The application of multi-criteria, decision-making tools and approaches can be used as a way of balancing trade-offs between environmental goals and life-cycle cost goals for both the agency and road users.

Strategies for Improving Sustainability of Pavement Preservation and Maintenance Activities

The general strategies for improving sustainability of preservation and maintenance treatments for concrete-surfaced pavements include limiting the use of new material, use of thinner cross sections, maintaining high levels of smoothness, and increased construction quality. These approaches all reduce environmental burden and contribute to more sustainable treatments. Significant differences may exist in the results of approaches that are used to reduce environmental impacts, depending on project-specific characteristics. For example, as traffic volume increases, maintaining smooth surfaces becomes more critical as the economic and environmental costs during the use phase begin to dominate the analysis. Although there is a clear distinction between agency costs and user costs with regards to economics, no such distinction exists when considering environmental impacts such as GHG and other emissions.

Integration of Preservation into Pavement Management Systems

The benefits of pavement management are well documented, and include: support for enhanced planning at the strategic, network and project levels; decision making based on observed and forecasted conditions rather than opinions; and the ability to generate alternate scenarios for future pavement conditions based on different budget scenarios or management approaches.

The integration of pavement preservation into pavement management requires a deliberate effort on the part of transportation agencies to re-evaluate their existing data collection activities, to revise and update performance modeling approaches, and to improve overall program development activities. The desired outcome is that the need for pavement preservation treatments and their timing of application can be identified within the pavement management system, and that the benefits realized from the application of the treatments can be accounted for in the system's optimization analysis.

SUSTAINABLE STRATEGIES FOR CONCRETE PAVEMENT END OF LIFE

When the pavement reaches its end of life, it may remain in place and reused as part of the supporting structure for a new pavement, recycled in place, or removed and recycled or landfilled. Each of these activities has an economic cost and an environmental impact (consumption of raw materials, energy input, emissions) that should be considered in the end-of-life (EOL) phase.

Reuse

The reuse of a material can be considered to include applications where the material is used in its current form, often in its current placement or location, with minimal (if any) processing. The suitability of a concrete pavement for reuse is controlled by the type, severity, and extent of the distresses that are present. The most common example of reuse of concrete pavement is when it is used without significant processing as a base or subbase layer for an overlay or new pavement structure. Rubblization of concrete pavement in preparation for the placement of an asphalt overlay can be considered to be reuse because the processing (rubblization) is not inherently necessary for the application but is one of several approaches for minimizing the potential for reflection cracking in the asphalt overlay due to the presence of joints and cracks in the underlying concrete.

The economic, environmental, and societal benefits of appropriately *reusing* the existing pavement structure are generally the highest of all end-of-life options for concrete pavements. There is great potential for material savings and conservation of resources, in terms of both the materials and energy required to produce and haul new materials, as well as reductions in the costs and energy associated with landfill disposal of old materials. In addition, construction duration is generally significantly shorter, resulting in reduced impacts to local users and businesses. These benefits may be partially (or even wholly) offset by shorter performance life or more frequent maintenance requirements in some cases, particularly when a reconstruction alternative would address foundation or drainage deficiencies in the existing structure. Further, changes in pavement grade or alignment generally preclude reuse. LCA, LCCA, and pavement performance analyses are useful in determining whether reuse of the concrete pavement is appropriate for any given situation.

Recycling

Crushed concrete or RCA can be used as a replacement for natural aggregate in many situations and applications. As quality aggregate sources are depleted, there is growing importance given to incorporating RCWMs even more aggressively in new and rehabilitated pavements. An ideal goal would be to use recycled materials to produce a long-lived, well-performing pavement and, at the end of its life, be able to use those materials again in a new pavement, effectively achieving a zero-waste highway construction stream. This would produce distinct cost advantages and would also provide significant reductions in energy consumption and GHG emissions while eliminating the need for landfill disposal.

The total amount of recycled concrete used in the U.S. is estimated to be 140 million tons (127 million MT) in 2014, including materials recycled from both pavements and other sources (CDRA 2014). These recycled materials can be used in new concrete or asphalt mixtures, as aggregate in base layers, as fill, riprap, and ballast, or in other uses. The distribution of the use of recycled concrete materials is shown in figure 8.

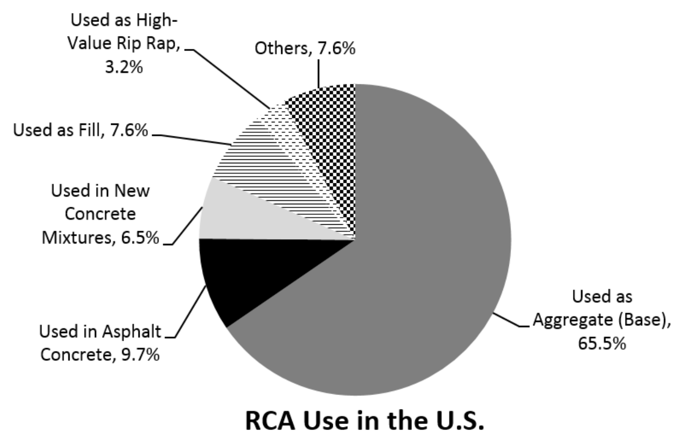


Figure 8. Recycling and reuse statistics for concrete materials (data compiled from Wilburn and Goonan [1998] and USGS [2000]).

> **A Strategy for Optimizing the Use of Recycled Materials**
>
> *Optimizing the use of recycled materials often implies its use in the highest possible value application (e.g., surface course aggregate as opposed to base or fill applications). However, the highest use is usually context-defined and may change over time as technologies continue to evolve and alternative recycling material implementation methods are developed.*
>
> *While experience shows that using recycled aggregate in a base can be cost-effective, other costs must be considered, including material handling, preparation for reuse, and transportation. Transportation is usually a relevant aspect from both a cost and environmental perspective; in general, on-site recycling or transporting recycled materials within a small radius is feasible. However, it may not be optimal to transport recycled materials over a long distance when a local primary source (or, sometimes, even when subprime materials are locally available). LCCA and LCA provide the means for determining the critical distance for transporting recycled materials compared to using local virgin materials to ensure efficiency and sustainability.*

RCA is a composite material comprising natural aggregate and hardened mortar. As such, RCA can have significantly different physical, mechanical, and chemical properties than natural aggregate, and these differences must be addressed in the material processing, pavement design, and construction phases of road projects. Some of the most important issues to consider are the quality and overall properties of the source concrete, the potential for short-term high alkalinity of RCA stockpile runoff and drainage from RCA foundation layers, the potential for calcium carbonate precipitate in edge drainage structures and on associated filter fabrics, the possible need to modify concrete mixture designs to account for RCA particle absorption and angularity, and the possible need to modify pavement structural designs (e.g., change slab thickness, joint spacing or reinforcing design) to account for differences in RCA concrete strength, shrinkage, thermal coefficient, etc. There are some excellent resources available to assist in addressing these issues (FHWA 2007; ACPA 2009).

Disposal

Disposal refers solely to the removal and hauling of a paving material to a landfill where it serves no purpose or value. Disposal costs are associated with demolition, transportation (which varies with haul distance), and landfill tipping fees, which vary widely and are increasing rapidly as available landfill space decreases (e.g., tipping fees increased from an average of $8/ton ($8.79/MT) in 1985 to $34.29/ton ($37.68/MT) in 2004 [Kuennen 2007]). One can also consider the potential value of RCA product (which can vary with the quality of the source concrete and the availability of local natural aggregate) as a lost value or opportunity cost of disposal.

Clearly, the economic and environmental costs of disposal are generally quite high and disposal is not an end-of-life option that will not often be preferred over the reuse and recycling options.

Economic and Environmental Considerations of EOL Options

Using materials from a pavement at the end of its life is accepted as one of the most effective ways to improve pavement sustainability. It is often true that, as noted previously, the economic, environmental, and societal benefits of appropriately *reusing* the existing pavement structure are generally the highest of all end-of-life options for concrete pavements, and that the economic and environmental costs of *disposal* are generally quite high. However, a comprehensive economic and environmental analysis for recycling and reusing pavement materials must be done in order to fully quantify the effects of the various EOL options. In order to realistically assess the benefits of the various EOL options, all options and their associated costs should be evaluated, including all of the factors that may potentially contribute to the costs and environmental implications of each. These important factors include technology (e.g., on-site or off-site processing), disposal costs (if any materials are to be landfilled), transportation, and the quality of the recycled material.

The reuse and recycling of concrete pavements results in economic and environmental impacts for both the old and new pavement structures. It is important, therefore, to properly *allocate* costs and benefits related to pavement reuse and recycling between the old and new pavement systems, taking care to avoid double counting in both systems.

Strategies for Improving End-of-Life Sustainability

The reuse of concrete pavements and the use of recycled concrete aggregate in lieu of natural aggregates are inherently sustainable activities, but there are strategies that can be employed to further increase their sustainability towards the ultimate goal of achieving a zero-sized waste stream at the pavement end of life (as well as for rehabilitation operations). These strategies include:

- *Optimizing the reuse and recycling of concrete pavement materials* through testing and characterization to use them in the highest feasible applications.
- *Adjusting RCA production operations to maximize production efficiency* (maximize product yield with minimum expenditure of effort and fuel consumption) through both customized preparation and breaking of the source concrete as well as through careful selection of the crushing and sizing operations.
- Making use of the value of RCA as a sink for the *sequestration of CO_2* (Gardner, Leipold, and Peyranere 2006).
- Making use of *on-site processing* and use of concrete paving materials whenever feasible (rather than hauling to an off-site facility for processing).

SUMMARY

This Tech Brief summarizes guidance concerning sustainability considerations for concrete pavement systems, as presented in detail in FHWA's recently published *Towards Sustainable Pavement Systems: A Reference Document* (FHWA 2015). Sustainability considerations throughout the entire pavement life cycle are examined, from material extraction and processing through the design, construction, use, maintenance/rehabilitation, and end-of-life phases, recognizing the importance of context sensitivity and assessing trade-offs in developing sustainable solutions.

Several of the strategies, technologies and innovations that have been presented are contributing to concrete pavement sustainability initiatives, including: reductions in energy and emission levels associated with the production and use of portland cement through increased use of SCMs, aggregates derived from RCWMs, and improved aggregate gradation, use of mechanistic-empirical design procedures for more effective pavement structural design, use of two-lift paving for improved use of local and marginal aggregates, adoption of construction practices that reduce fuel use and GHG emissions while improving construction quality, proper application of low-environmental-impact pavement preservation and preventive maintenance activities to prolong pavement life and defer major rehabilitation and reconstruction activities, and increased utilization of recycled concrete materials in the highest feasible applications.

REFERENCES

American Concrete Pavement Association (ACPA). 2003. *Slag Cement and Concrete Pavements*. RT No. 4.03. American Concrete Pavement Association, Skokie, IL. (Web Link).

American Concrete Pavement Association (ACPA). 2006. *Pavement Surface Characteristics: A Synthesis and Guide*. EB235P. American Concrete Pavement Association, Skokie, IL.

American Concrete Pavement Association (ACPA). 2008. *Concrete Pavement Field Reference: Pre-Paving*. EB237P. American Concrete Pavement Association, Skokie, IL.

American Concrete Pavement Association (ACPA). 2009. *Recycling Concrete Pavements*. EB043P. American Concrete Pavement Association, Skokie, IL.

American Concrete Pavement Association (ACPA). 2010. *Concrete Pavement Field Reference: Paving*. EB238P. American Concrete Pavement Association, Rosemont, IL.

American Society of Civil Engineers (ASCE). 2010. *Structural Design of Interlocking Concrete Pavement for Municipal Streets and Roadways*. ASCE Standard 58-10. American Society of Civil Engineers, Reston, VA.

Antonucci, N. D., K. K. Hardy, J. E. Bryden, T. R. Neuman, R. Pfefer, and K. Slack. 2005. *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan. Volume 17: A Guide for Reducing Work Zone Collisions*. NCHRP Report 500. Transportation Research Board, Washington, DC.

Association of Environmental Professionals (AEP). 2012. *California Environmental Quality Act (CEQA) Statute and Guidelines*. Association of Environmental Professionals, Palm Desert, CA.

Brand, A., J. Roesler, I. Al-Qadi, and P. Shangguan. 2012. *Fractionated Reclaimed Asphalt Pavement (FRAP) as a Coarse Aggregate Replacement in a Ternary Blended Concrete Pavement*. ICT-12-008, UILU-ENG-2012-2014. Illinois Center for Transportation, Urbana, IL.

Chai, L., C. L. Monismith, and J. Harvey. 2009. *Re-Cementation of Crushed Material in Pavement Bases*. UCPRC-TM-2009-04. California Department of Transportation, Sacramento, CA.

Choate, W. T. 2003. *Energy and Emission Reduction Opportunities for the Cement Industry*. U.S. Department of Energy, Washington, DC. (Web Link).

Construction and Demolition Recycling Association (CDRA). 2014. *Good Economic Sense*. Construction and Demolition Recycling Association, Aurora, IL. (Web Link).

Environmental Protection Agency (EPA). 2010. *Post-Construction Stormwater Management in New Development and Redevelopment*. Environmental Protection Agency, Washington, DC. (Web Link).

Environmental Protection Agency (EPA). 2015. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013*. EPA 430-R-15-004. Environmental Protection Agency, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2007. *Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement*. Technical Advisory T 5040.37. Federal Highway Administration, Washington, DC.

Federal Highway Administration (FHWA). 2012. *Pervious Concrete*. Tech Brief. FHWA-HIF-13-006. Federal Highway Administration, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2014. *Pavement Sustainability*. Tech Brief. FHWA-HIF-14-012. Federal Highway Administration, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2015. *Towards Sustainable Pavement Systems: A Reference Document*. FHWA-HIF-15-002. Federal Highway Administration, Washington, DC. (Web Link).

Ferrebee, E. C. 2014. *Development of the Materials, Construction, and Maintenance Phases of a Life Cycle Assessment Tool for Pavements*. Master Thesis. University of Illinois, Urbana, IL.

Gardner, K. H., J. Leipold, and S. C. Peyranere. 2006. *Concrete Carbonation*. Project 12 Final Report. Recycled Materials Resource Center, University of New Hampshire, Durham, NH.

General Accounting Office (GAO). 2013. *Federal-Aid Highways: Improved Guidance Could Enhance States' Use of Life-Cycle Cost Analysis in Pavement Selection*. Report to Congressional Committees, GAO-13-544. General Accounting Office, Washington, DC. (Web Link).

Harrington, D. 2008. *Guide to Concrete Overlays: Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements*. Second Edition. National Concrete Pavement Technology Center, Ames, IA.

Harrington, D. and G. Fick. 2014. *Guide to Concrete Overlays. Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements*. Third Edition. National Concrete Pavement Technology Center, Ames, IA. (Web Link).

Heckel, L. 2002. *Rubblizing with Bituminous Concrete Overlay - 10 Years' Experience in Illinois*. IL-PRR-137. Illinois Department of Transportation, Springfield, IL.

Henry, J. J. 2000. *Evaluation of Pavement Friction Characteristics*. NCHRP Synthesis 291. Transportation Research Board, Washington, DC.

Hoerner, T. E., K. D. Smith, H. T. Yu, D. G. Peshkin, and M. J. Wade. 2001. *PCC Pavement Evaluation and Rehabilitation, Reference Manual*. NHI Course No. 131062. National Highway Institute, Arlington, VA.

Jones, D., J. T. Harvey, H. Li, T. Wang, R. Wu, and M. M. Campbell. 2010. *Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements:* Final Report. UCPRC-Davis, Davis, CA. (Web Link).

Kendall, A. 2012. "Time-Adjusted Global Warming Potentials for LCA and Carbon Footprints." *International Journal of Life Cycle Assessment*. Volume 17, No. 3. Springer, Berlin Heidelberg, New York, NY.

Keoleian, G., A. Kendall, J. Dettling, V. Smith, R. Chandler, M. Lepech, and V. Li. 2005. "Life Cycle Modeling of Concrete Bridge Design: Comparison of Engineered Cementitious Composite Link Slabs and Conventional Steel Expansion Joints." *Journal of Infrastructure Systems*. American Society of Civil Engineers, Reston, VA.

Kosmatka, S. and M. Wilson. 2011. *Design and Control of Concrete Mixtures: The Guide to Applications, Methods, and Materials*. 15th Edition. EB001.15. Portland Cement Association, Skokie, IL.

Kuennen, T. 2007. "The Economics of Recycling." *Rock Products*. Volume 110, Number 10. Mining Media, International, Denver, CO.

Lee, E. B., J. T. Harvey, and M. M. Samadian. 2005. "Knowledge-Based Scheduling Analysis Software for Highway Rehabilitation and Reconstruction Projects." *Transportation Research Record 1907*. Transportation Research Board, Washington, DC.

Lobo, C. and G. M. Mullings. 2003. "Recycled Water in Ready Mixed Concrete Operations." *Concrete in Focus*. Spring 2003. National Ready Mixed Concrete Association, Silver Spring, MD.

Morian, D., T. Van Dam, and R. Perera. 2012. *Use of Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete Pavements*. FHWA-HIF-12-008. Federal Highway Administration, Washington, DC.

National Asphalt Pavement Association (NAPA). 1994. *Guidelines for Use of HMA Overlays to Rehabilitate PCC Pavements*. Publication IS-117. National Asphalt Pavement Association, Lanham, MD.

Santero, N. 2009. *Pavements and the Environment: A Life-Cycle Assessment Approach*. Doctoral Thesis. University of California, Berkeley.

Santero, N. and A. Horvath. 2009. "Supplemental Information: Global Warming Potential of Pavements." *Environmental Research Letters*. Vol. 4. No. 3. IOP Publishing, Bristol, England, UK.

Scott, S., L. Konrath, T. Ferragut, S. Anderson, I. Damnjanovic, G. Huber, J. Katsafanas, K. McGhee, M. Sprinkel, C. Ozyildirim, B. Diefenderfer, D. Merritt, D. Dawood, K. Molenaar, M. Loulakis, D. White, and V. Schaeffer. 2014. *Performance Specifications for Rapid Highway Renewal*. SHRP2 S2-R07-RR-1. Transportation Research Board, Washington, DC. (Web Link).

Smith, D. R. 2011. *Permeable Interlocking Concrete Pavements Manual - Design, Specification, Construction, Maintenance*. Fourth Edition. Interlocking Concrete Pavement Institute, Herndon, VA.

Smith, K. D., D. A. Morian, and T. J. Van Dam. 2012. *Use of Air-Cooled Blast Furnace Slag as Coarse Aggregate in Concrete Pavements-A Guide to Best Practice*. FHWA-HIF-12-009. Federal Highway Administration, Washington, DC.

Smith, K. D., H. T. Yu, and D. G. Peshkin. 2002. *Portland Cement Concrete Overlays: State of the Technology Synthesis*. Federal Highway Administration, Washington, DC.

Smith, K. L., K. D. Smith, L. D. Evans, T. E. Hoerner, M. I. Darter, and J. H. Woodstrom. 1997. *Smoothness Specifications for Pavements*. NCHRP Web Document 1. Transportation Research Board, Washington, DC.

Smith, R., E. Ferrebee, Y. Ouyang and J. Roesler. 2014. "Optimal Staging Area Locations and Material Recycling Strategies in Sustainable Highway Reconstruction." *Computer-Aided Civil and Infrastructure Engineering*. *Vol. 29*. John Wiley and Sons, New York, NY.

Taylor, P. C., S. H. Kosmatka, G. F. Voigt, M. E. Ayers, A. Davis, G. J. Fick, J. Grove, D. Harrington, B. Kerkhoff, H. C. Ozyildirim, J. M. Shilstone, K. Smith, S. Tarr, P. D. Tennis, T. J. Van Dam, and S. Waalkes. 2006. *Integrated Materials and Construction Practices for Concrete Pavements: A State-of-the-Practice Manual*. FHWA-HIF-07-004. Federal Highway Administration, Washington, DC.

Thompson, M. R. 1989. *Breaking/Cracking and Seating Concrete Pavements*. NCHRP Synthesis 144. Transportation Research Board, Washington, DC.

Torres, H. N., J. Roesler, R. O. Rasmussen, and D. Harrington. 2012. *Guidance for the Design of Concrete Overlays Using Existing Methodologies.* National Concrete Pavement Technology Center, Ames, IA.

Transportation Research Board (TRB). 2006. *Rubblization of Portland Cement Concrete Pavements*. TR Circular E-C087. Transportation Research Board, Washington, DC.

U.S. Department of Transportation (USDOT). 2006. *National Strategy to Reduce Congestion on America's Transportation Network.* U.S. Department of Transportation, Washington, DC.

U.S. Geological Survey (USGS). 2000. *Recycled Aggregates - Profitable Resource Conservation*. USGS Fact Sheet FS-181-99. U.S. Geological Survey, U.S. Department of the Interior, Washington, DC. (Web Link).

Van Dam, T. 2010. *Tech Brief: Geopolymer Concrete*. FHWA-HIF-10-014. Federal Highway Administration, Washington, DC. (Web Link).

Van Dam, T. and K. Smith. 2011. *Tech Brief: Blended and Performance Cements*. FHWA-HIF-10-025. Federal Highway Administration, Washington, DC. (Web Link).

Van Dam, T., P. Taylor, G. Fick, D. Gress, M. VanGeem, and E. Lorenz. 2012. *Sustainable Concrete Pavements: A Manual of Practice*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.

Wang, T., I.-S. Lee, J. Harvey, A. Kendall, E. B. Lee, and C. Kim. 2012. *UCPRC Life Cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance*. UCPRC-RR-2012-02. (Web Link).

Wilburn, D. and T. Goonan. 1998. *Aggregates from Natural and Recycled Sources-Economic Assessments for Construction Applications*. Circular 1176. U.S. Geological Survey, U.S. Department of the Interior, Washington, DC. (Web Link).

Zapata, P. and J. A. Gambatese. 2005. "Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Construction." *Journal of Infrastructure Systems*. Vol. 11. American Society of Civil Engineers, Reston, VA.

Contact: For more information, contact:

Federal Highway Administration (FHWA)
Office of Asset Management, Pavements and Construction
Gina Ahlstrom (Gina.Ahlstrom@dot.gov)

Researcher: This Tech Brief was developed by Mark B. Snyder (Consultant), Tom Van Dam (NCE), Jeff Roesler (University of Illinois, Urbana-Champaign), and John Harvey (University of California, Davis), and prepared under FHWA's *Sustainable Pavements Program*. Applied Pavement Technology, Inc. of Urbana, Illinois served as the contractor to FHWA.

Distribution: This Tech Brief is being distributed according to a standard distribution. Direct distribution is being made to the Divisions and Resource Center.

Availability: This Tech Brief may be found at http://www.fhwa.dot.gov/pavement.

Key Words: concrete pavements, sustainability, sustainable strategies, sustainability best practices, pavement life-cycle

APRIL 2016 FHWA-HIF-16-013