TechBrief

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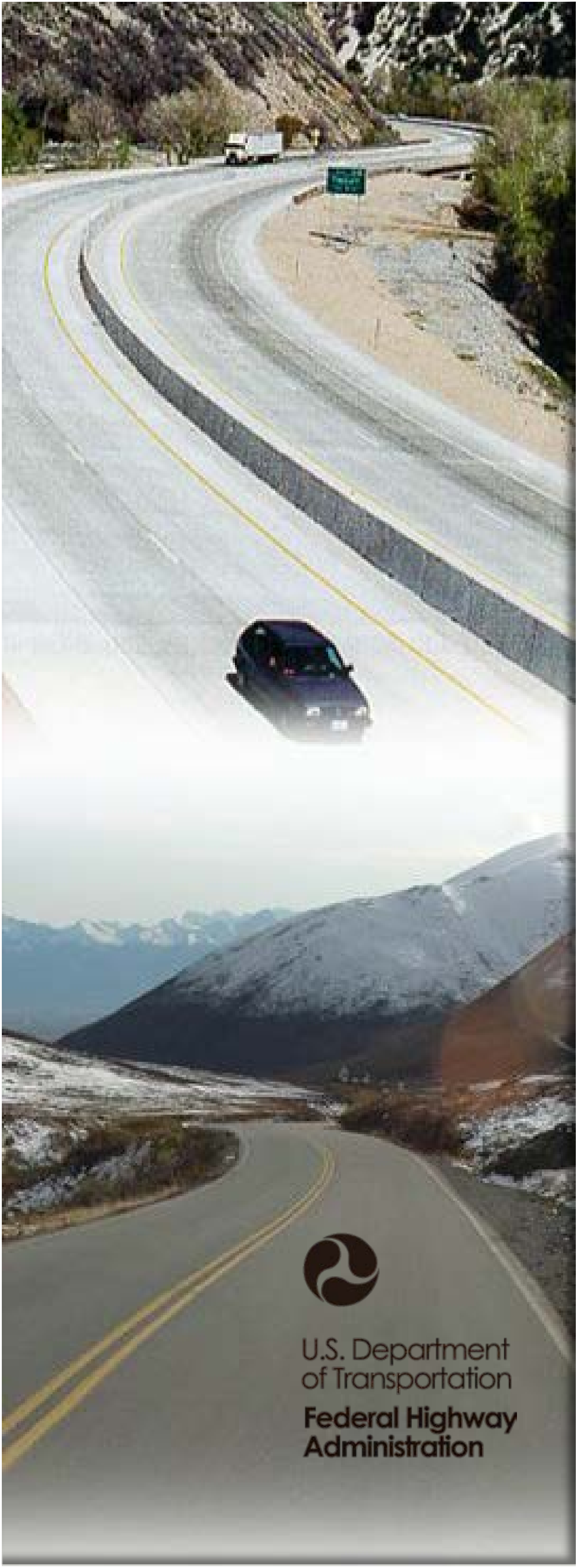
PAVEMENT SUSTAINABILITY



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, but in recent years significant efforts are being made to quantify sustainability effects and to incorporate them in a more systematic and organized fashion.

The purpose of this *Tech Brief* is to present 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 technology and trends.

WHAT IS A SUSTAINABLE PAVEMENT?

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.

Pavement Sustainability Best Practices

This *Tech Brief* highlights processes, actions, and features that improve on existing practices. 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.

Integrating Sustainability into Pavements

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 and precedence.

THE PAVEMENT LIFE CYCLE

Six key pavement life-cycle phases are considered for sustainability best practices, as illustrated in figure 1 and described below (Santero 2009; UCPRC 2010):

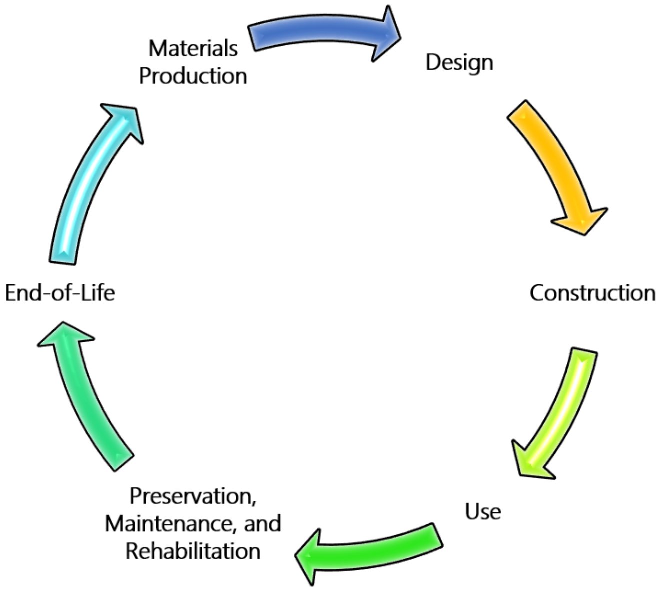


Figure 1. Pavement life-cycle phases.

- **Materials production**. Activities involved in pavement materials acquisition (e.g., mining, crude oil extraction) and processing (e.g., refining, manufacturing, mixing), including plant processes and transport.
- **Pavement design.** The process of identifying the functional requirements of a pavement, gathering relevant information (e.g., subgrade, traffic, weather), and then selecting and specifying materials and the pavement structural composition. The design of unpaved roads is not addressed in this *Tech Brief*.
- **Construction.** Processes and equipment associated with the construction of pavement systems, including both new construction and reconstruction efforts.
- **Use.** Pavement characteristics (e.g., roughness, stiffness/rigidity, and macrotexture) that affect vehicle energy consumption and corresponding emissions as well as the surrounding environment (e.g., hydraulic flow retention/detention and contamination, air emissions, noise, heat capacity/conductivity, solar absorptivity, sound absorptivity).
- **Preservation, maintenance, and rehabilitation**. The application of treatments to an existing pavement that slows the rate of deterioration or that addresses functional or structural deficiencies.
- **End-of-life.** The final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its performance life.

Note that most sustainability best practices and processes are interrelated and can have impacts—sometimes even opposing impacts—in several different phases of the life cycle.

MEASURING SUSTAINABILITY

In many instances, it is useful to measure pavement sustainability in order to quantify, manage, or improve upon current practices. Four general measurement methods can be used to quantify various aspects of sustainability:

- **Performance assessment.** This entails assessing overall pavement performance in relation to its intended function and specified physical attributes deemed necessary to meet that function. Examples of performance assessment include condition ratings, pavement structural capacity, pavement ride quality, and frictional characteristics in support of safety. Most often, performance is addressed in relation to the current standard practice, with the most common sentiment being that alternatives must have equal or better performance than the current standard practice.
- **Life-cycle cost analysis (LCCA).** This is an economic analysis that is used to evaluate the total cost of an investment option over its entire life (Walls and Smith 1998). Most State DOTs practice LCCA to some degree in selecting the preferred pavement alternative for major projects (Rangaraju, Amirkhanian, and Guven 2008), although LCCA is not practiced for all pavement projects. Various software tools are available to assist in the analysis, with the FHWA's *RealCost* (FHWA 2011) being most prevalent (Rangaraju, Amirkhanian, and Guven 2008).
- **Life-cycle assessment (LCA).** This is a technique that can be used to analyze and quantify the environmental impacts of a product, system, or process. LCA, in particular as applied to pavements, is an evolving field of study. The International Standards Organization (ISO) provides overarching guidance for LCA, but specific standards for use with pavements are still being developed. Therefore, pavement LCA results must be carefully scrutinized since their data sources and system boundaries (that is, what processes are and are not considered) tend to vary between individual tools and studies. Consequently, LCA in its current state can be effectively used to quantify improvements made to a specific type of pavement but should be used cautiously in comparing two different pavement types due to differences in data sources and system boundaries.

- **Rating systems.** Rating systems are essentially lists of sustainability best practices with an associated common metric. This metric, usually points, allows each best practice to be quantified and compared using a common unit. Rating systems can vary greatly in quality and use; in its simplest form, a rating system can count every best practice equally (e.g., all worth one point), in which case the rating system amounts to a tally of the number of best practices used. More often, some type of weighting is used where one or more points are assigned to a best practice based on the level of its perceived positive impact. Generally, rating systems address more than just pavements, although several of the more popular ones include many pavement-related items. FHWA's INVEST (www.sustainablehighways.org) and Greenroads (www.greenroads.org/) are two examples of mature sustainable highways rating systems that include pavements.

IMPACTS

Pavement sustainability best practices can have varying levels of impact on a pavement system and on surrounding systems, which means that they are not all equal. Some best practices can result in large changes in environmental, social, and economic impact factors, while others result in only small changes. In addition, there are some best practices that impact multiple sustainability components over the long term (e.g., a 40- or 50-year analysis period), while others focus on one or two specific sustainability considerations and may only have impact during a single life-cycle phase. For instance, a long-life pavement design can impact materials use, pavement condition (thus, affecting traffic and fuel efficiency), and construction activities over a typical 40- to 50-year analysis period (LCA, as a metric, could be used to roughly quantify these effects for certain key environmental indicators such as energy use and emissions). On the other hand, reducing emissions from construction vehicles only has impact during times of active construction (a relatively short impact over a 40- to 50-year analysis period). This does not, however, imply a universal hierarchy of best practices. Rather, sustainability is context sensitive so an organization or project should select and apply sustainability best practices that are consistent with its desired sustainability goals and appropriate for the conditions at the location and time in which they are operating.

FRAMEWORK FOR CONSIDERING TRADE-OFFS

Since sustainability is a broad system characteristic encompassing virtually every system impact, it can be argued that most pavement features and qualities support sustainability goals in some way or another. However, it is unlikely that all such features can be included in a given pavement because either (1) some features support one sustainability objective but are in opposition to another, or (2) some features are mutually exclusive. Thus, there are trade-offs associated with the inclusion/exclusion of sustainability best practices within a given pavement system. This section describes a few key items to be considered when evaluating trade-offs. Even if benefits and costs are difficult to quantify, it is important to use a consistent framework in analyzing trade-offs to avoid introducing unintended bias. In general, this framework involves consideration of the following:

- **Priorities and values of the organization or project.** If an agency's sustainability goals and priorities exist and are clearly articulated, the first-order trade-off consideration is to favor the feature that best supports those goals and priorities. However, identification of sustainability goals and priorities for transportation organizations is still in its infancy so they may not exist. In such instances, other considerations may be more important.

- **Performance.** Performance, or the ability to serve an intended use, is the traditional means of measuring a pavement's benefit. A common (if not narrow) first-order performance consideration is how a particular pavement alternative compares to the current standard practice. However, other considerations may justify a reduction in performance in order to capture other benefits.

- **Cost and benefit.** Economic considerations are the traditional means of measuring a pavement's cost and/or benefit, and pavement benefits are traditionally assumed equal for the alternatives being considered over a given analysis period. To enhance sustainability, economic considerations should be viewed over the entire life cycle of the pavement to include initial construction, maintenance/preservation, rehabilitation, and end-of-life. LCCA, discussed earlier, is the typical means to quantify pavement economic considerations.

- **Impact magnitude and duration.** For any particular metric, the magnitude and duration of a sustainability best practice's effects should be considered. Generally, positive effects of greater magnitude and duration are more highly valued. In some cases, LCA can be used to quantify and compare environmental impacts, but in other cases quantification is difficult if not impossible. In these cases, it may be enough to determine the general duration of impact (e.g., just during construction, over the entire life of the pavement) in order to make a decision.

- **Risk.** Generally, "risk" means that there is some uncertainty regarding the impact and cost of a selected alternative and such uncertainty leaves open the possibility of less desirable outcomes than predicted. Tools that provide a probabilistic-based analysis (e.g., *RealCost* [FHWA 2011] and

Construction Analysis for Pavement Rehabilitation Strategies—*CA4PRS* [Caltrans 2008]) can help quantify risk due to uncertainty. Some metrics, like LCA, are only now beginning to incorporate uncertainty into their analysis.

- **Broad impacts in time and space.** Many pavement decisions and features can have broad impacts beyond their immediate purpose. For instance, an open-graded friction course (OGFC) may be used to reduce tire-pavement noise and improve friction, but under some conditions it may have a shorter service life than a conventional overlay resulting in additional construction activity and materials use in the long-term. While this is a classic trade-off scenario, it may not be readily apparent if an analysis of trade-offs only considers factors present during initial construction (e.g., costs) or in the first several years of service (e.g., 2 to 4 years). Ultimately, limiting the scope of a trade-off analysis may result in unintended consequences. The risk of unintended negative consequences is greatest when changes are made that affect one part of a system or life-cycle phase, but the effects of the changes on the rest of the system and the other life-cycle phases are not evaluated.

SUSTAINABILITY BEST PRACTICES

The following sections briefly present pavement sustainability best practices organized by the pavement life-cycle phases. In general, most organizational approaches to sustainability involve rethinking priorities and ultimately placing more emphasis on the social and especially the environmental components of sustainability (Muench et al. 2012). The sustainability best practices described here reflect that and, therefore, typically involve activities that result in life-cycle reductions in any or all of (1) the quantities of non-renewable resources consumed either as fuel or as direct materials, (2) the amount of greenhouse gas (GHG) emissions generated, and (3) the ecological impacts. The current approach in these efforts is largely focused on doing “less harm” than previous practices, whether that is to human well-being or to the environment or ecological systems; as a result, there is a strong emphasis on reducing negative impacts (e.g., energy use, GHG emissions, non-renewable resource depletion). However, a process solely focused on reducing negative impacts can unintentionally lose focus on the greater goal: creating processes that have positive impacts.

In many instances, decisions based on economic costs and benefits, such as the cost of materials, fuel, water, waste disposal, and operations, will provide a good proxy for decisions based on much broader sustainability principles. Yet economics fails as a sustainability proxy when external costs are not included in the analysis or current market costs. Environmental impacts (especially large-scale ones that cannot be traced to a single source or cause) and resource depletion are notoriously undervalued (if considered at all) in simple economic analyses. Furthermore, some costs that are considered may in fact be subsidized (e.g., energy, water) or borne by others outside the scope of the analysis (e.g., off-shore production).

Materials

The energy consumption and emissions generated through the acquisition, processing, and transportation of materials used in the construction, maintenance, and rehabilitation of pavements impact the overall sustainability of the system. Pavement materials also have a significant influence on pavement performance over the design period and thus directly contribute to impacts incurred during the use phase.

In general, sustainability best practices for materials typically involve one or more of the following:

- Reducing the use of virgin material in favor of various recycled, co-product, and waste materials (RCWMs).
- Reducing the use of virgin material through improved mix design and increased longevity.
- Reducing the impacts of materials production by improving efficiency and reducing emissions.

In most cases, if performance is not adversely affected, these sustainability best practices will be primarily driven by economics. For example, when focused on initial cost, economic considerations tend to favor RCWMs and improved production efficiency. This illustrates that the key to successful implementation of sustainability best practices is to identify opportunities for enhancement in which the economics are maintained or improved while environmental and social impacts are reduced over the life cycle.

Aggregates

Aggregates make up the largest share of the mass and volume in a pavement structure (see figure 2), whether used without binding material (e.g., unbound subbase or base material), or as part of an asphalt or hydraulic cement bound layer. Although aggregates are relatively low cost and have a relatively low environmental impact per unit mass, they have a significant impact on pavement sustainability because they are consumed in large quantities, are a non-renewable natural resource, and increasingly cannot be mined near their point of use.

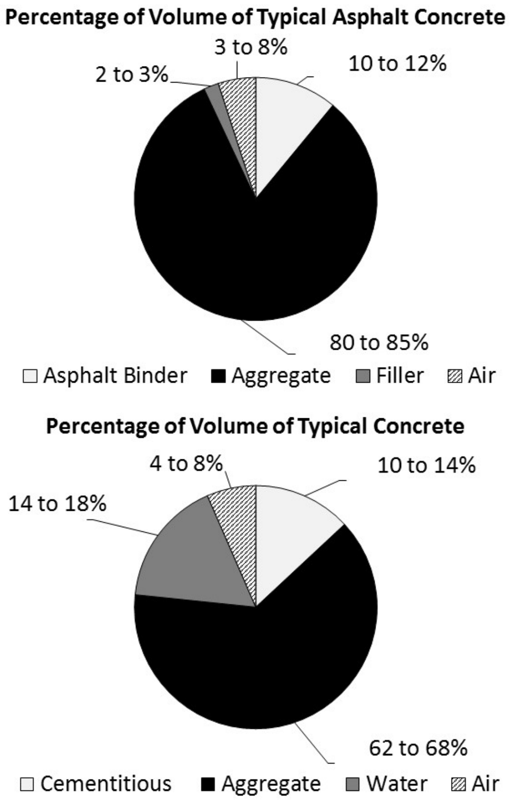


Figure 2. Typical volumes of aggregates in dense-graded asphalt concrete and in dense-graded hydraulic cement concrete (asphalt concrete: summary of mixture designs by authors; concrete: Tayabji, Smith, and Van Dam 2010).

Furthermore, whether obtained from hard rock quarries or mined as sand and gravel from alluvial sources, aggregate acquisition and processing affects the local environment and surrounding communities. Aggregate sustainability best practices include:

- **Reduce virgin aggregate content by increasing the use of aggregates derived from RCWM sources**, including reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), air-cooled blast furnace slag (ACBFS), steel furnace slag (SFS), recycled asphalt shingles (RAS), and foundry sand, all while ensuring that pavement performance is not compromised.
- **Minimize aggregate transportation and/or optimize the modes of transportation used (barge, rail, or truck).** This reduces the energy and emissions associated with transport and generally results in making maximum use of locally available aggregate sources.

New aggregate sources are often located a great distance from urbanized areas, which eases the societal burden of quarry or pit location but incurs perhaps more environmental burden due to increased transport distances. This has resulted in aggregate scarcity in some locations. Some urban areas that have river, lake, or sea access (such as Detroit, the San Francisco Bay Area, Chicago, and Los Angeles) overcome this problem by importing aggregate to urban processing plants using low-impact marine transportation. Such practices, however, tend to shift impacts geographically rather than eliminate or lessen them.

Asphalt Materials

Asphalt materials, including both binders and asphalt concrete mixtures, have evolved significantly in recent years, with increased amounts of RAP and RAS being used to replace virgin binder and aggregate. Additives to either the asphalt binder (e.g., polymers, crumb rubber from used tires) or to the entire mixture (e.g., fibers) are becoming more common as owners seek ways to increase pavement life by improving resistance to fatigue and plastic deformation and increasing overall durability. Many specialized asphalt concrete mixtures can be created to specifically address sustainability concerns like drainage, safety, and noise. Asphalt and asphalt concrete sustainability best practices include the following:

- **Reduce virgin binder content in asphalt concrete by increasing the use of RAP and RAS**. Both RAP and RAS are RCWMs that contain asphalt, and can be effective in reducing the amount of virgin binder used in a mixture.

- **Use alternatives fuels to reduce non-renewable energy consumption and GHG emissions associated with mixture production.** Many asphalt plants can use waste oil (e.g., cooking oil, used oil) as a fuel. When used properly, waste oil can replace other non-renewable fuel sources and can be less expensive.
- **Reduce the energy and emissions associated with mixture production by adopting WMA technologies.** Within the U.S., the use of WMA is increasing rapidly (see figure 3), with the use of plant foaming techniques currently dominating (Hansen and Copeland 2014). Many producers actually use WMA techniques without reducing mixing temperature because of the improved aggregate coating and compaction efficiency they provide.
- **Use additives to extend pavement surface life**. This includes using polymer-modified and crumb rubber-modified binders. WMA additives can be used to reduce compactive effort and decrease construction impacts while also potentially increasing the overall level of compaction, thus leading to an increase in pavement life.

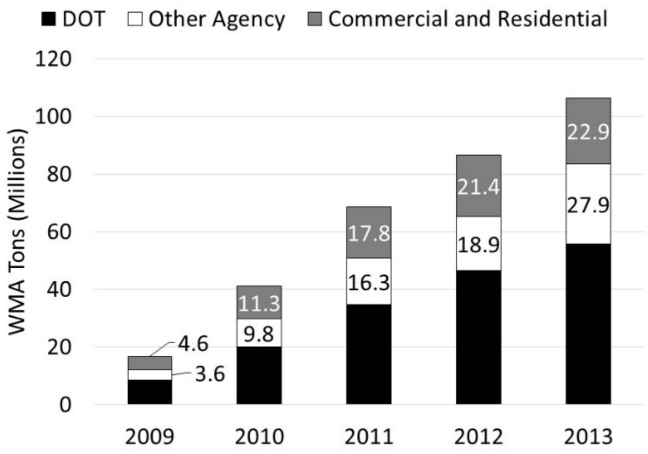


Figure 3. Estimated tons of WMA by industry sector, 2009–2012 (Hansen and Copeland 2014).

- **Reduce transportation impacts by using locally available materials and in-place recycling.** This can often mean using locally available marginal aggregates over imported higher quality aggregates deeper within the pavement structure so that performance is not compromised.
- **Use open-graded mixtures for sustainability purposes.** OGFCs are being used in a number of states (e.g., California, Arizona, Alabama, and Georgia, to name just a few) to improve tire-pavement friction, reduce tire-pavement noise, and reduce splash and spray effects.

Concrete Materials

The versatility of concrete materials continues to improve with the adoption of technologies that positively enhance sustainability. Still, the major challenge facing hydraulic cement concrete is that the production of the primary binder (portland cement) is energy- and GHG-emission-intensive. Reductions in energy and emission levels are best met by expanding efforts to reduce the amount of portland cement used in paving mixtures over the life cycle. Concrete materials sustainability best practices include:

- **Reduce the amount of portland cement in paving mixtures.** This can be accomplished by using a lower total cementitious material content through improved aggregate grading, using AASHTO M 295 blended cements (in which portland cement clinker is partially replaced with supplementary cementitious materials [SCMs] such as fly ash, slag cement, and/or ground limestone), increasing the use of SCMs added at the concrete plant, and improving the durability of concrete mixtures to extend pavement life. Figure 4 shows fly ash production, use, and utilization rate from 1996 to 2011 and the overall trend suggests significant increase in production and use.

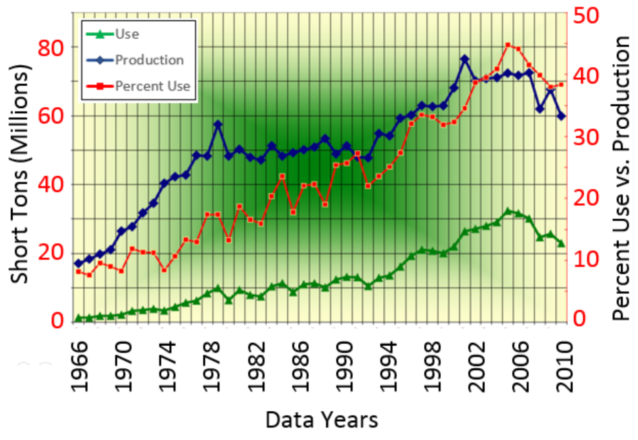


Figure 4. U.S. fly ash production, use (U.S. short tons), and utilization rate from 1966 to 2011 (ACAA 2013) (Note: 1 short ton = 0.907 metric ton).

- **Reduce water use in concrete production through the recycling of washout water.**
- **Reduce transportation impacts by using locally available materials and RCWMs.** This can often mean using locally available marginal aggregates over imported higher quality aggregates within the pavement structure (e.g., in the bottom lift of a two-lift concrete pavement) so that performance is not compromised.
- **Improve plant efficiency and use alternatives fuels to reduce non-renewable energy consumption and GHG emissions associated with portland cement clinker and concrete production.** The Environmental Protection Agency's (EPA's) Energy Star program certifies cement plants that use energy most efficiently. Similarly, some concrete ready mix plants are certified by the National Ready Mix Concrete Association's (NRMCA's) *Sustainable Concrete Plant Certification* program (see www.nrmca.org/sustainability/Certification/PlantCertification.asp).

Pavement Structural Design

Sustainability best practices for pavement structural design generally consist of (1) considering the entire pavement life cycle when making key decisions (economic, environmental, social, or other), (2) using innovative pavement types and materials (described below) to address one or two key sustainability issues on a project, and (3) improving the structural design through the use of new tools or a better understanding of design parameters and performance. Pavement design sustainability best practices include:

- **Use improved mechanistic-empirical (ME) pavement design procedures.** ME pavement design procedures, such as the AASHTOWare Pavement ME Design Software (AASHTO 2012), can produce more efficient pavement designs with acceptable performance by better accounting for specific traffic, climate, and other design conditions for the project. ME design permits better integration of materials and pavement design, as well as better consideration of construction quality requirements.

- **Optimize the use of materials within the pavement structure.** Pavement designs that optimize the use of materials and cross sections that meet performance requirements while achieving environmental and economic benefits are particularly attractive alternatives. This often means using higher cost/impact materials where most needed (e.g., the surface layer) and using lower cost/impact materials deeper in the pavement structure. Longer lasting designs that may use somewhat more material initially but less material over the life cycle typically enhance sustainability. Knowledge of fundamental properties of the materials used and recent advances in construction practices to achieve specific design requirements will help produce more sustainable pavement designs.
- **Incorporate LCCA, LCA, and rating systems into the pavement design process.** These tools can provide economic, environmental, and other best practices input into the overall design process. Moreover, several key use-phase issues, such as smoothness, surface friction, noise, and stormwater management, can be considered in the design stage to help address later use-phase impacts.
- **Consider specialty designs to address prominent sustainability issues.** There are a number of designs that may address specific sustainability issues for a given project, including structural designs that maximize the use of RCWMs and local materials, fast-track construction, noise-reducing surfaces, modular pavement systems (including concrete paver blocks), pavement strategies for stormwater management, and consideration of use-phase impacts in the design phase. For example, permeable pavements, which use open-graded mixtures for the entire structure, can be used to contribute to low impact development (LID) drainage solutions (Prince George's County 1999). Such practices are typically limited to low-volume pavements, parking areas, and shoulders. Many cities and some state highway agencies are now adopting LID solutions as the first consideration in drainage design (e.g., City of Seattle 2009; Washington State DOE 2012), and the EPA continues to strongly support what they call "green infrastructure" or LID solutions (EPA 2013).

Construction Considerations to Improve Pavement Sustainability

Most construction activities have less sustainability impacts than other life-cycle phase activities because construction constitutes a relatively short amount of time in the total pavement life cycle and often does not influence later phases. An exception to this is construction quality, which can have far-reaching implications through the end-of-life phase. Sustainability best practices for construction typically include (1) allowing sustainability best practices to be used, (2) reducing fuel consumption, energy use, and GHG emissions attributed to construction activities, and (3) improving construction quality. Pavement construction sustainability best practices include:

- **Create, modify, and use specifications that allow for sustainability best practices.** Construction specifications need to be evaluated to ensure that they are not a barrier to improved sustainability. Many specifications contain arbitrary barriers that limit the use of RCWMs, for example, and thus prevent reductions in environmental savings over the life cycle. Agencies are encouraged to evaluate their existing specifications in light of current knowledge to remove barriers to increased sustainability.
- **Reduce the negative impacts associated with construction.** This includes fuel consumption, exhaust emissions, particulate generation, and noise directly associated with construction activities as well as construction-related traffic delays and congestion. Furthermore, the area surrounding the construction site is also affected by the pavement construction, possibly impacting residents, businesses, and local ecosystems.
- **Optimize or improve efficiency of construction activities.** This considers improvements in pavement construction that may be realized through the optimization of construction planning and sequencing, management of construction-related traffic delays, reduced construction noise, better waste management, and using new construction techniques and equipment such as two-lift concrete paving (see figure 5), spray pavers in asphalt overlay construction (see figure 6), and automated machine guidance, to name a few. At the same time, regulations require continued improvements in the operation efficiency of construction equipment, lowering combustion emissions such as volatile organic carbon (VOC) and nitrous oxide (NO_x) emissions, diesel particulates, and fugitive particulate matter.

Figure 5. Two-lift concrete paving (image credit: Peter Taylor).

Figure 6. Spray paver used in asphalt overlay construction (Al-Qadi et al. 2012).

- **Improve construction quality.** Quality is an essential element in constructing a durable pavement and, consequently, is fundamental to improving its overall sustainability. Improved construction quality can result in a major reduction in the number of maintenance and rehabilitation treatments, with a corresponding reduction in negative impacts during the life cycle. Furthermore, construction specifications can play a key role in incentivizing long-term quality. A number of innovative technologies are being adopted to improve construction quality and monitoring, including techniques such as intelligent compaction, stringless paving, infrared thermographic scanning, and real-time smoothness measurements. Constructing smooth pavements has both short-term and long-term sustainability benefits, especially for facilities carrying high traffic volumes.

Maintenance and Preservation Practices

Currently there is limited information that directly quantifies the sustainability impacts of pavement maintenance and preservation practices, yet it is widely accepted that maintenance and preservation strategies that keep good pavements in good condition enhance sustainability. Generally, sustainability benefits are derived in the following ways: (1) maintenance and preservation keep smooth pavements smooth longer, which result in better fuel efficiency for users (Chatti and Zaabar 2012; Lidicker et al. 2012), and (2) maintenance and preservation extend the service and structural life of pavements leading to less material use over the life of the pavement. Maintenance and preservation sustainability best practices include:

- **Incorporating sustainability metrics into current asset management systems.** As sustainability metrics increase in importance, they should be tracked in asset management tools. This will provide a means to benchmark measures already taken against previous sustainability performance and more readily identify opportunities for further improvement. Critical factors for consideration in selecting a suitable maintenance or preservation treatment and its timing includes pavement condition (and trends), performance history of the treatments, overall performance needs or requirements, construction constraints, LCCA, and LCA.
- **Understanding the life-cycle implications of maintenance and preservation treatments.** Understanding complete life-cycle impacts is an essential element in establishing the advantages and disadvantages of any given treatment. Unfortunately, available data are not currently sufficient to support detailed environmental analyses. However, other information is available on pavement preservation, including succinct summaries of preservation treatments, applications, and effectiveness (Peshkin et al. 2011).
- **More intensive use of pavement maintenance/preservation methods known to extend pavement life while maintaining pavement smoothness.** For asphalt pavements, some surface treatments and thin overlays have been found to be effective whereas dowel bar retrofitting and diamond grinding can be used to restore the surface characteristics of concrete pavements.

End-of-Life Considerations

End-of-life strategies have a large impact on the sustainability of both asphalt and concrete pavements because they usually involve a large volume of material with significant potential for reuse or recycling. Typically sustainability best practices involve (1) avoiding or delaying end-of-life, and (2) increasing recycling/reusing techniques. End-of-life sustainability best practices include:

- **Consider design, rehabilitation, maintenance and preservation strategies that allow pavements to continue to function without requiring an end-of-life scenario.** In most situations, continuing to use or reuse pavements in acceptable condition is preferable to recycling or disposing of old pavements. Strategies such as long-life pavement design, properly timed overlays (asphalt or concrete), and timely maintenance/preservation activities that restore or maintain smoothness can help a pavement avoid an end-of-life scenario that requires further processing or waste. Such activities extract the maximum utility from the materials already in place and tend to avoid more costly—and more energy/emission intensive—recycling or disposal operations.

- **Avoid landfilling old pavement materials.** Landfilling as an end-of-use option is becoming less attractive because of the value associated with recycling and reusing pavement demolition products as well as dwindling landfill space. Landfilling is an extremely infrequently used end-of-life option.
- **Consider in-place reuse/recycling techniques.** Some techniques allow the reuse or recycling of material in-place such as hot in-place recycling, cold in-place recycling, full-depth reclamation, and crack/seat and overlay. These techniques, while not as sustainable as continued use or reuse, do keep the original materials in-place (thereby saving on transportation costs, energy, and emissions) and allow them to contribute to a new pavement structure; overall, this saves materials and time when compared to a pavement structure constructed with entirely new materials.
- **Consider the "highest use" of recycled materials.** The "highest use" refers to the preferred use of a recycled material in order to extract the greatest payback in terms of sustainability. This requires the consideration of all of the costs (economic, environmental, and social) involved in recycling and using a particular material. Under such an approach, a material such as RAP, for example, would find its highest use as a replacement for both binder and aggregate in a new asphalt mixture instead of being used as an aggregate base where the inherent advantage of the binder in the RAP would not be fully exploited. This approach also considers the costs of transporting materials and landfilling to ensure that materials are employed according to their highest value.
- **Increase the use of reclaimed material in new pavements.** RAP and RCA have an established track record of use in new pavements, both in new asphalt and new concrete structures, as well as in unbound base layers. This is illustrated in figure 7, which indicates the usage of these materials in various pavement applications. Recycling processes can be conducted on-site (thus, saving transportation costs, energy and emissions) or off-site (e.g., at central plants or facilities). The impacts, both economic and environmental, should be accounted for when considering the use of RAP and RCA in new pavements. For instance, in some rural scenarios, the distance to suitable RAP or RCA sources (or other RCWMs) may be prohibitively long and increase the cost or energy/emissions compared with much closer virgin sources.

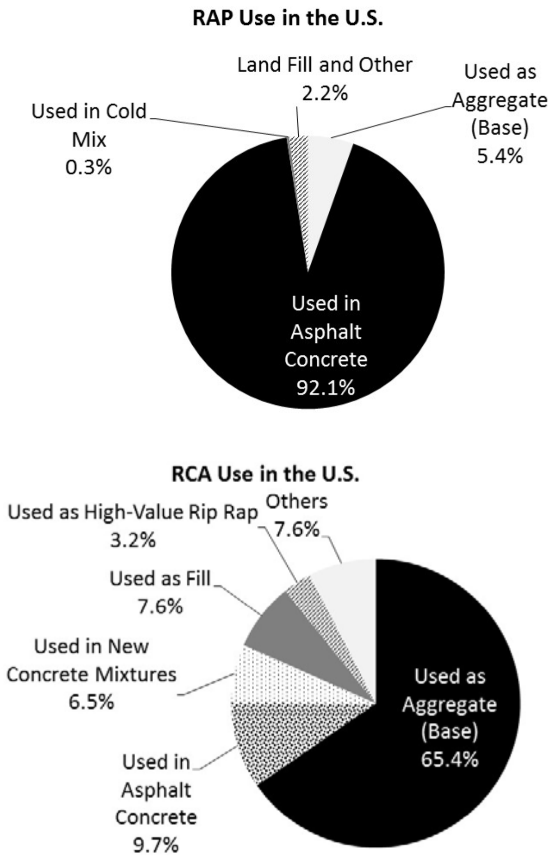


Figure 7. Recycling and reuse statistics of asphalt and concrete materials (data compiled from Hansen and Copeland [2014] for RAP and from Wilburn and Goonan [1998] and USGS [2000] for RCA).

SUMMARY

This *Tech Brief* provides a summary on how to incorporate sustainability considerations into the pavement life cycle. Recognizing that the purposeful implementation of pavement "sustainability" has just begun, there are a number of opportunities that exist today that can help facilitate that journey. In that vein, several of the strategies, technologies, and innovations that are contributing to pavement sustainability initiatives are summarized as follows:

- **RCWM use at higher rates of replacement.** While the use of RCWMs (e.g., RAP, RCA, RAS) has been a long-standing practice, the rates of use have often been limited by design procedures, technology, construction specifications, performance risk (perceived or real), and availability. Recent trends have driven owners, designers, and contractors to explore ways of incorporating more locally available RCWMs at greater replacement levels. Rethinking mixture design processes, manufacturing requirements, specification limits, and construction practices from the ground up has already led to higher rates of use and better acceptance of RCWMs in pavements. As an added benefit, the reduced virgin material use and associated reductions in processing and transport can result in significant energy consumption and GHG emission reductions. The key to successfully implementing this strategy is to ensure that increasing RCWMs content does not result in an unexpected decrease in pavement performance.

- **Adoption of WMA technologies as standard practice.** For asphalt pavements, WMA has received much attention in both technology improvement and implementation. Documented benefits of reduced energy consumption, reduced emissions (GHG and others), and improved construction quality have been primary drivers in the expanded use of WMA, and this trend should continue.
- **Increased use of SCMs to reduce concrete GHG emissions.** The concrete industry has continued to reduce GHG emissions by reducing the portland cement content per unit volume of concrete while providing equal or better performance. Cement manufacturers are producing a greater variety and amount of blended cements (AASHTO M 295) using SCMs and/or interground limestone to further reduce GHG emissions. Mixtures containing less than 50 percent portland cement of the total cementitious content are available and have shown good performance when used appropriately. As the use of SCMs, portland-limestone cements, and concrete mixtures containing less cement per unit volume gain more acceptance by highway agencies, significant reductions in GHG emissions associated with concrete pavement construction will be attained.
- **ME pavement design procedures.** Improved pavement designs are being implemented as state highway agencies adopt ME pavement design methodologies. ME design is based on a better understanding of pavement materials and construction quality and response to traffic and environmental loadings, more definitively linking those responses to pavement performance. The utilization of ME pavement design allows broader thinking and the consideration of materials and design approaches beyond what can be considered using a traditional empirical approach, thus providing a means for innovation.
- **Optimized materials use.** Two-lift concrete pavements and long-life asphalt pavements are examples of design approaches that optimize the use of paving materials to meet specific needs. For example, two-lift pavements can use higher recycled or marginal aggregate content in a thicker bottom lift while reserving more durable material for the thinner surface lift, thereby reducing the environmental impact of the overall structure without compromising performance. Similarly, long-life asphalt pavements can select specific mixture properties for the various layers to increase the use of recycled materials while ensuring enhanced long-term performance.
- **Construction technologies.** A number of emerging construction technologies are resulting in the production of higher quality, longer lasting pavements that can have significant environmental, economic, and social benefits. Intelligent compaction, stringless paving, and real-time smoothness measurements are a few technologies that are providing real-time data to contractors. These data allow them to better control their processes to achieve improved in-place material properties and higher levels of initial pavement smoothness. Construction specifications that incentivize long-term quality and remove barriers to more sustainable practices encourage innovation while reducing the frequency of future maintenance and rehabilitation treatments.
- **Expanded use of preservation treatments.** Preservation treatments that use little material yet maintain pavements in a smooth condition for longer periods of time have great environmental benefit, especially on higher traffic volume roadways. This realization makes the use of ultra-thin asphalt surfaces and diamond grinding of concrete pavements particularly attractive.

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