# 13. PAVEMENT SUSTAINABILITY

Human activities and world development practices are affecting the economic, environmental, and social health of the planet. As a result, virtually all businesses, corporations, and industries have been challenged to adopt practices that maintain economic vitality while at the same time balancing critical—and often competing—environmental and societal needs. The transportation industry, like other businesses and industries, is attempting to respond to this need, but at the present time faces substantial budget deficits and an aging pavement network that is seeing ever-increasing traffic volumes and vehicle loadings. The problem is especially acute in urban areas, where deteriorated infrastructure, obsolescent facilities, and serious congestion problems are resulting in economic loss, environmental damage, and societal harm.

Consequently, those responsible for the nation’s pavements are overwhelmed, recognizing that the current approach to addressing the crisis facing our pavement network is not sustainable. What is needed is a new approach, one that results in reduced economic cost over the life cycle, lessens environmental impact, and enhances societal benefit of the system into perpetuity. In response to this change in mindset, many transportation agencies are adopting practices that are beginning to rate, incentivize, and even award projects based on their demonstrated ability to enhance sustainability. Yet, the basic question remains: what is “sustainability” and what can be done to enhance the sustainability of pavements?

### What is Sustainability?

Sustainability is commonly defined as the capacity to maintain a process or state of being into perpetuity without exhausting the resources upon which it depends nor degrading the environment in which it operates. In the context of human activity, the United Nations (UN) has described sustainability as activity or development “that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). Sustainability must consider economic, environmental, and social interests over an extended period of time, forming what is commonly referred to as the “triple-bottom line.” Sustainable activities are those that create a workable balance between these three factors, as they are often in conflict with one another. Graphically, this concept is expressed in Figure 13-1, which illustrates that sustainable solutions are those that incorporate all elements of the triple-bottom line.

Although conceptually simple, the application of sustainability principles to pavement problems is very difficult. Balancing economic, environmental, and societal interests for a pavement project requires identifying specific factors that represent each interest, collecting data and applying tools to quantify the impact of each factor, and assessing the combined impact of the factors in relationship one to another. Complicating the process is that factors must be identified and measured/estimated during all stages of a pavement’s life—design, materials selection, construction, operation, preservation/rehabilitation, and reconstruction/recycling. Moreover, the importance of different factors and considerations will vary from project to project. As a result of the complexity, it is recognized that a complete assessment of sustainability is beyond the current state-of-the-practice and in truth, may be an impossible endeavor. Yet the application of available tools will assist in making incremental progress to achieving more sustainable pavements.



Figure 13-1. Graphical representation of sustainability’s “triple-bottom line” of economic, environmental, and societal interests.

As society moves toward increased sustainability, it is important to understand the current approach used in the decision-making process. Until fairly recently, decision-making with regards to industrial activity was largely based on consideration of the “bottom-line,” which was understood to reflect purely economic factors. Few paid attention to degrading social and environmental conditions under this model of industrial activity, as achieving immediate tangible economic goals was rewarded while ignoring long-term, broader system needs was largely done without consequence (Senge et al. 2008). The result was the creation of an economy that is highly dependent on the use of non-renewable energy and material resources, inefficient and waste-generating production, and economic growth driven through the consumption of products and services.

As an alternative, Senge et al. (2008) suggests that the economy must make greater use of harvested renewable resources while dramatically reducing accumulating waste. Waste generated from industrial processes must be used either as nutrients for ecological systems to support natural resource development or as raw materials in other industrial processes. This will result in industrial activity in which resources are largely regenerated and waste minimized or eliminated, establishing a close link between economic growth and natural resource regeneration. Ideally, the economic system will mimic that which happens in nature, in which the concept of waste is eliminated and all waste becomes food for other processes (McDonough and Braungart 2002).

As described previously, inherent in the sustainability concept is that the economic, environmental, and social benefits and costs of any product or service are considered over its entire life cycle. In the pavement arena, pavement “life” is conventionally thought of as being linear, moving from the “cradle” (design, material extraction and processing, and construction) through its service life and finally to the “grave,” where the pavement is removed and reconstructed. This cradle-to-grave concept is counter to true sustainability considerations, which instead stipulate a “cradle-to-cradle” approach in that the end-of-life is part of a new beginning (McDonough and Braungart 2002). For pavements, this is shown in Figure 13-2, illustrating how the design, materials processing, construction, operations, preservation and rehabilitation, and reconstruction and recycling are joined in a continuous loop. During the pavement design development process, pavement designs should try to balance all sustainability aspects.



Figure 13-2. The pavement life cycle ([Van Dam and Taylor 2009](http://www.cproadmap.org/publications/sustainability_briefing.pdf)).

Applying sustainability principles at a practical, implementable level using today’s technologies simply means finding opportunities to minimize environmental impact while increasing economic and social benefit. Already, the value of life cycle cost analysis (LCCA) is recognized as a way to consider current and future anticipated economic impacts over the life of the design ([FHWA 2011a](http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm)). In addition, a number of approaches to assess pavement sustainability are emerging and will soon be available for implementation. By stepping away from the larger issues of the economy as a whole, and instead focusing on the project level, these overarching sustainability concepts will be implemented into actionable and measureable activities that will be useful to the pavement industry.

To do so, it is essential to recognize that a pavement can be considered as a project-level system embedded within larger systems. The pavement project-level system has its own context which is sensitive to the needs defined by the various stakeholders (e.g. owner/agency, public, contractor, materials supplier, and so on) and the environmental setting in which the project is to be constructed ([Muench et al. 2011](http://www.greenroads.us/14/manual.html)). Already, there has been movement within the pavement industry to adopt practices that support sustainability at the project-level that have broader system-wide sustainability impacts. For example, a common waste product now routinely used in concrete production is slag cement, which is an industrial byproduct (waste) that with little processing can be used to improve the long-term properties of concrete (meeting project-level needs) while lowering the carbon footprint of the constructed pavement (reducing system-wide environmental impact). Similarly, the use of reclaimed asphalt pavement (RAP) in new asphalt mixtures is an excellent implementation of “cradle to cradle” principles in which the existing pavement structure is regenerated for use in the new pavement structure. In both these examples, the triple-bottom line is addressed, as the options are economically viable while being environmentally and socially beneficial.

### Why Should the Pavement Industry Care About Sustainability?

Sustainability is nothing new. It simply represents good engineering, entailing working under fixed constraints (e.g., materials, resources, construction windows) to achieve an overall objective. What has changed is the scope of the problem and the period of time over which the project is evaluated. Whereas in the past economic factors were paramount, sustainability requires that environmental and social factors be equally considered. Furthermore, the span of time considered in the analysis includes the entire life cycle of the project, including all impacts (both positive and negative) that occur from the point of inception (e.g. mining of raw materials for example) through the use phase (when the project is in service) to its end-of-life (e.g. recycling). At this juncture, sustainable design is not about perfection, but instead about balancing the various interests to incrementally bring about change. As sustainability practices continue to evolve, so will the role played by the pavement industry, doing its part to create a truly sustainable transportation infrastructure.

One of the driving forces for improving the sustainability of pavements is the public’s growing awareness that a sustainably built environment is achievable, requiring civil engineers to examine alternative solutions that a few years ago might not have been considered. This belief is clearly annunciated in the integrated global aspirational vision statement adopted at the 2006 *Summit on the Future of Civil Engineering*, which stated that civil engineers are “entrusted by society to create a sustainable world and enhance the global quality of life” (ASCE 2007). This is a significant aspiration, reflecting the responsibility entrusted by the public to those charged with designing, constructing, operating, preserving, rehabilitating, and recycling infrastructure including pavements. More directly relevant to the pavement industry is that various agencies, from local cities and counties, to State Departments of Transportation, and to the Federal Highway Administration (FHWA), are all embracing the need to become more sustainable and some are beginning to require that sustainability metrics be measured on pavement projects.

Another important reason for adopting sustainability is that it will make the pavement industry more attractive to a younger, motivated workforce. The American Society of Civil Engineers (ASCE) recognizes that civil engineers are perceived to be part of the problem, as reflected by the last sentence in the 2009 Board of Direction’s statement “Civil engineers are not perceived to be significant contributors to a sustainable world (ASCE 2009)”. It is also known that employees, particularly recent graduates, make career choices based on a company’s or industry’s commitment to sustainability (Senge et al. 2009). With this backdrop, it is clear the industry can change negative perceptions and attract the young talent needed for the future by advancing pavement sustainability.

And finally, the adoption of sustainability principles will make the pavement industry more innovative and competitive. This can already be observed through such diverse innovations as in-place recycling of existing pavement, warm-mix asphalt (WMA), concrete made with high supplementary cementitious material (SCM) content, perpetual asphalt pavement, two-lift concrete pavement, and permeable pavement surfaces, to name a few. As will be seen, each of these examples clearly demonstrates scenarios having positive economic, environmental, and social impacts. Emerging pavement technologies are poised to bring even more dramatic positive changes. The challenge to the industry is to step out of the box and “re-imagine” what a pavement can be, while working with the various stakeholders to improve the sustainability inherent in the pavement network.

## Sustainability Factors

This section describes the most common economic, environmental, and societal factors used to assess pavement sustainability. It is understood that these factors are often linked and at times overlap.

### Economic Factors

The recommended approach to considering the economic factors for project specific pavement applications is the use of LCCA. In an LCCA, not only is the initial cost of the pavement considered, but discounted future costs for maintenance and rehabilitation are also part of the analysis. Further, the recommended analysis period for a pavement application is long, typically 40 to 50 years, and thus the future cost of reconstruction must also be added. And finally, rarely does the end of pavement life correspond with the end of the analysis period, so the discounted “salvage” value of the pavement at the end of the analysis period must also be included. Two equivalent economic indicators are the equivalent uniform annual cost (EUAC) and the Net Present Value or Present Worth.

Often, LCCA is done in a deterministic way and only considers the cost to the transportation agency. Both of these can limit the value of the analysis. However, it is well known that many of the variables included in the analysis (e.g., the discount rate, future maintenance/rehabilitation timing and costs, salvage value, and so on) are not fixed values, and may in actuality be different from that assumed in a deterministic analysis; this can significantly affect the results of the LCCA. At the same time, although agency costs are important, in many cases user costs (e.g., user delay, increased vehicular maintenance, decreased fuel efficiency due to road roughness, and so on) should not be ignored as part of the analysis in order to more accurately assess the economic impact of pavement decisions.

The FHWA’s RealCost program is a good example of a user-friendly and powerful software tool that can be used for LCCA ([FHWA 2011a](http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm)). It can evaluate pavement alternatives using a deterministic or probabilistic approach, and allows the inclusion of simplified user costs in the analysis. The use of such a tool can help describe the economic factors of interests from a sustainability perspective.

### Environmental Factors

The environmental factors are less defined than the economic factors and are often open to interpretation and debate. Yet there is a solid scientific basis for most environmental impact categories and indicators, and much of the required data and analytical tools are available to conduct objective and repeatable analysis to achieve consistent results. The environmental impact must be considered over the entire life cycle, using the same analysis period as is used for the LCCA. Often, accurate assessment of the environmental impact of some of the earliest phases, such as material acquisition and processing, lack location specific, up-to-date detailed data that would readily support project level assessment. In addition, environmental impact incurred during the use phase is sometimes difficult to quantify as there are many unknowns. Yet overall there is consensus that sufficient data and analytical tools are available to make reasonable broad environmental assessments to improve the sustainability of pavements. Environmental factors might include greenhouse gases or dust produced in manufacture of materials, blending of components of the pavement layer, construction laydown for initial construction and subsequent treatments to the roadway.

### Societal Factors

Societal factors are often of the highest importance yet are the least understood of the three principles of sustainability. Societal benefit is central to the planning of civil infrastructure such as pavements, yet there are almost always “winners” and “losers” when it comes to major infrastructure projects. For example, a major expansion of a roadway can result in positive social impact for some through increased accessibility and mobility, but can easily translate into a negative for those in communities immediately adjacent to the project who will be impacted by increased traffic, noise, and pollution.

The FHWA’s [Livability Initiative](http://www.fhwa.dot.gov/livability/) represents one element of the contribution pavements play in meeting societal needs. Livability initiatives are aimed at “improving community quality of life while supporting broader sustainability goals” and include community design, land use, environmental protection and enhancement, mobility and accessibility, public health, and economic well-being ([FHWA 2011b](http://www.fhwa.dot.gov/livability/state_of_the_practice_summary/research2011.pdf.)). In this definition, the overlapping of economic, environmental, and societal factors is evident, yet it is clear that healthy communities require both a healthy economy and healthy environment. Good choices with regards to pavement design and materials can contribute to positive societal impact by increasing safety, reducing noise, and improving water quality, amongst others. Stakeholder participation in the design process and ensuring that the local context for the project is accounted for are essential elements in improving the societal impact of a pavement project.

## General Strategies for Improving Pavement Sustainability

The implementation of sustainable solutions requires that the preceding economic, environmental, and societal factors be considered over the life cycle of the pavement. Currently, pavement type selection is based on the structural and functional needs of the facility and incorporation of sustainability is typically considered after the pavement type has been selected. The following general strategies can be employed on any pavement project to improve the sustainability:

* Use an analysis period that is longer than the typical pavement design life. A 50-year analysis period has become common when conducting pavement sustainability assessments, although it may be as short as 35 years for low-volume roadways or as long as 75 years for high-volume, long-life pavement sections. A life-cycle perspective is essential to implementing sustainable solutions, as it has been demonstrated that alternatives that initially appear to be sustainable but fail to meet design life expectations actually have decreased overall sustainability due to higher life cycle costs and environmental impact ([Ram et al. 2011](http://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC1550_354975_7.pdf)).
* The economic LCCA should carefully consider all initial and future anticipated costs influenced by the alternatives being considered (e.g., no need to include costs for elements that will remain constant for all alternatives being considered) following the best practices (see [FHWA LCCA](http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm) website). The analysis should be conducted considering both agency costs and user costs, and both a deterministic and probabilistic analysis should be conducted. Furthermore, a sensitivity analysis to determine the significance of the various inputs should be run. In the end, the significance of observed differences must be determined and the results carefully evaluated as part of the overall assessment.
* A pavement design that meets the desired project needs, neither under-designing nor over-designing, creates an efficiency that supports sustainability. It is beneficial to also use pavement designs that recognize the influence of material choices on sustainability and allow increased use of low emission/low energy materials. Methods and materials that reduce noise also support sustainability.
* All things equal, materials choices that reduce the carbon footprint and energy consumption over the analysis period are less environmentally damaging, and thus more desirable from a sustainability perspective. Within practical limits, selecting materials that maximize the use of recycled or industrial byproduct materials (RIBMs) can be one way to minimize environmental impact. Furthermore, because transportation is associated with significant economical and environmental costs, ways of reducing material transportation costs, including the use of more efficient modes of transportation (e.g., rail and barge transportation have lower environmental cost than truck transportation), should be considered in the evaluation.
* Future maintenance and rehabilitation activities have a strong influence on sustainability; thus, those strategies that minimize traffic disruption while restoring serviceability, while at the same time minimizing the use of non-renewable resources, typically have the most positive influence on sustainability.
* While in service, pavements must have minimal negative impact on the user as well as the surrounding communities and natural environment. From a user perspective, safety and vehicle operating costs are two of the most important considerations, both of which are known to be directly related to pavement ride quality. For example, for a given surface texture, pavements that are constructed smooth and remain smooth with adequate friction will be safer and have reduced vehicle operating costs including maintenance and lower fuel consumption. Similarly, quieter pavements are important, especially in an urban setting, and such pavements should be constructed and maintained at quieter noise levels over time. Other considerations for in-service pavements might include aesthetics, reflectivity, porosity and permeability, among other factors.
* At the end of life, the pavement must be readily recyclable, and no part of it should be transported to a land-fill. However, this may not always be possible and should be accounted for in the life-cycle assessment (LCA). End-of-life planning is thus an essential element in creating sustainable pavements.

The above strategies are applicable to both asphalt pavement systems and concrete pavement systems. The next two sections describe practices applicable to asphalt and concrete pavements for improving the sustainability of those specific systems.

## Sustainable Practices for Asphalt Pavements

Based on the factors previously described, the following demonstrated practices can be used to improve the sustainability of asphalt pavements.

### Sustainable Asphalt Pavement Design

The AASHTO Pavement-METM mechanistic-empirical pavement design procedure combines key material properties with technologically advanced design computations to develop competent pavement designs that are neither under- or over-designed (see [Pavement-ME](http://www.aashtoware.org/Pages/DARWin-ME.aspx) website). Multiple materials can be considered including hot mix asphalt, WMA, chemically- and asphalt-treated layers, and unbound layers. Consequently, various low-emission, low-energy materials can be incorporated into various layers of the pavement system, thereby maximizing the use of local materials and those featuring high RIBMs content. Specific design strategies that should be considered to improve asphalt pavement sustainability include:

* Increased use of chemically- or asphalt-treated supporting layers that maximize the use of RIBMs including recycled aggregate, fly ash, slag cement, emulsions, and so on. Pavement-METM allows the unique properties of these materials to be included in the design process.
* Increased use of perpetual pavement in which only surface renewal is required over the long-life of the pavement resulting in significant life cycle economic and environmental savings (see [NAPA Perpetual Pavement](http://www.hotmix.org/index.php?option=com_content&task=view&id=193&Itemid=317) website).

### Sustainable Asphalt Pavement Material Selection and Construction

Prudent material selection and acute construction practices have a significant impact on improving the sustainability of asphalt pavements. Specific strategies that have been implemented in the asphalt area include the following:

* Increased use of reclaimed asphalt pavement (RAP). Asphalt is the most commonly recycled pavement in the U.S., with approximately 100 million tons of old asphalt pavement reclaimed each year (of which 60 percent is recycled back into new asphalt mixtures and 40 percent is used in other pavement applications) ([NAPA 2009](http://www.hotmix.org/images/stories/sustainability_report_2009.pdf)). RAP is composed of approximately 95 percent aggregate and 5 percent asphalt binder, the latter which is rejuvenated when the RAP is used in new asphalt mixtures. Thus, all things being equal, increasing the amount of RAP used in new asphalt mixtures is an excellent strategy to improve the overall sustainability of asphalt pavements, providing adequate performance and surface characteristics like friction are obtained. This can be done without negatively impacting construction or pavement performance through more frequent use of RAP and striving to use it on all asphalt pavement projects. Laboratory testing is required to insure that the mixtures can meet the performance standards. Increasing the amount of RAP allowed as a percent of the asphalt mixture is another strategy that should be explored. The percent RAP allowed can be increased through better characterization/processing of the RAP (in a process called fractionation), through the use of increased RAP percentages in lower pavement lifts, through improved mixture processing, and potentially through the adoption of WMA technology. One of the largest barriers to increasing the percent RAP allowed is the preponderance of outdated construction specifications that do not recognize some of the advances that have been made to increase the amount of RAP that can be included in a new mixture. The FHWA maintains a website providing the latest guidance on the use of RAP in asphalt pavements (see [FHWA Asphalt Pavement with RAP](http://www.fhwa.dot.gov/pavement/recycling/rap/index.cfm) website).
* Increased use of WMA (see [NAPA Warm-mix Asphalt](http://www.warmmixasphalt.com/) website). During the mix production phase, heating aggregate and binder to mixing temperatures is the single largest consumer of energy and creator of emissions. As such, reducing the processing temperature of asphalt mixtures from the normal asphalt range of around 320 oF to a range of 212 oF to 280 oF typical of WMA can have significant positive impact ([NAPA 2009](http://www.hotmix.org/images/stories/sustainability_report_2009.pdf)). In addition to environmental benefits, WMA technologies have the added benefit of extending the construction season in northern climates, and extending the compaction window once a mixture is placed. A number of different WMA technologies exist and development continues with this exciting technology. Some are based on asphalt foaming techniques (using synthetic zeolite or water added at the plant), others employ chemical additives that reduce internal friction, while a third type of WMA technology incorporate rheological modifiers (based predominately on waxes). As these technologies continue to develop, it is important that both the life cycle costs and environmental impacts be considered to ensure that benefits derived during the construction phase are not reduced or eliminated due to costs incurred in the production and transportation of some of the WMA additives.
* Increased use of other RIBMs in asphalt pavement construction. Chemically treating supporting layers with fly ash or slag cement is one way to increase the use of RIBMs in asphalt pavement construction. In addition, the use of recycled concrete aggregate (RCA), slag aggregate, and/or foundry sand is another way to increase RIBMs use. The most advantageous strategy is to use RIBMs that replace/supplement asphalt binder, including ground tire rubber (GTR) and recycled asphalt shingles (RAS). GTR has been used for decades, but is seeing a resurgence as recognition grows of its positive attributes that include increased pavement longevity, reduced pavement noise, and reduced vehicular breaking distance ([EPA 2011](http://www.epa.gov/osw/conserve/materials/tires/ground.htm)). Although less common than GTR, the use of RAS in asphalt mixtures continues to grow as advantages to recycling both pre-consumer and post-consumer shingles. Notable successes by the Illinois Tollway Authority will help eliminate some of the barriers to RAS that currently exist at the state transportation agency level ([Bentsen 2010](http://www.cdworldmag.com/index.php/features/161-illinois-tollway-authority-jump-starts-asphalt-shingle-recycling-in-the-state.html)).
* Increased use of in-place recycling. In this process, the existing deteriorated pavement is pulverized, shaped, and compacted in place with or without the use of a stabilizer and/or additional aggregate. In-place recycling effectively eliminates the economic and environmental costs associated with acquiring new materials for the base and its transport, as well as the removal, transport, and disposal of the waste material. The use of asphalt emulsions or RIBMs such as fly ash offer additional environmental savings.

Regardless of the materials choices made, transporting “sustainable” materials great distances by trucks will have significant negative economic and environmental impact. Thus the environmental impact of transporting materials must be considered in the decision-making process.

### Sustainable Asphalt Pavement Maintenance and Rehabilitation

Numerous maintenance and rehabilitation strategies are available to keep asphalt pavements in good serviceable conditions. Strategies that can have the greatest positive impact on sustainability are those that 1) maintain smoothness and surface friction while minimally disrupting traffic operations, and 2) use the least amount of non-renewable, high-energy, high-emission materials. The following are example strategies that meet those requirements:

* Pavement preservation and repair strategies – these include a number of non-structural treatments designed to keep good pavements in good condition. Inherently such treatments require only short lane closure times or can use moving lane closure operations. Applicable treatments include including crack sealing and filling, minimal patching, thin surface treatments, and surface recycling techniques (see [Pavement Preservation](http://www.pavementpreservation.org/) website). The latter two treatments can be used to restore a safe riding surface if required.
* Thin asphalt overlays can be effectively used to treat existing asphalt pavements to address non-structural deficiencies ([Newcomb 2009](http://www.hotmix.org/images/stories/is-135.pdf)). Thin overlays can be placed in conjunction with cold-milling, in which a “mill and fill” strategy incorporating RAP from the existing pavement is used in the new overlay, providing surface renewal at great efficiency. Thin overlays typically have higher economic and environmental costs than surface treatments or surface recycling techniques and thus must be used appropriately. The use of thin asphalt overlays on structurally deficient pavements results in premature failure and is a non-sustainable practice.
* Pavements suffering from structural deficiencies can be rehabilitated with a structural overlay of sufficient thickness to carry anticipated future traffic loading. Rehabilitation with a structural overlay can be designed using AASHTOware Pavement-METM, which can consider both asphalt and concrete overlays. Poor rehabilitation design can result in premature failure of the overlay at significant economic and environmental costs so care must be exercised during rehabilitation design.

### Sustainable Asphalt Pavements In-Service

Although great focus is placed upon material selection, construction, maintenance, and rehabilitation, upwards of 90 percent of the energy and emissions associated with a pavement are incurred due to the operation of vehicles during its service life. Furthermore, the pavement’s interaction with the surrounding community and environment go well beyond the energy consumed and emissions generated by the passing vehicles. Thus, achieving improved sustainability of in-service asphalt pavements can be realized through implementation of the following:

* Construct and maintain asphalt pavements in a smooth condition; vehicles operating on smooth pavements have reduced operating costs, improved fuel efficiency, and reduced emissions.
* Construct and maintain quieter pavement surfaces that will minimize impact on the surrounding community. This is particularly important for high-speed facilities in urban areas but has value even in rural areas. The use of stone-matrix asphalt (SMA) or open-graded friction courses have been shown to significantly reduce noise (see [NAPA Quiet Pavement](http://www.hotmix.org/index.php?option=com_content&task=view&id=194&Itemid=319) website).
* Use patterned asphalt and stains to creating aesthetically pleasing pavements that can be clearly demarcated for various uses (e.g., traffic lanes, pedestrian crosswalk, bike lane, and so on). This is most important in urban areas (see [Caltrans Roadside Management Toolbox](http://www.dot.ca.gov/hq/LandArch/roadside/detail-sac.htm) website).
* Consider the use of colored asphalt and light aggregates and/or porous asphalt in areas where urban heat island (UHI) effects are of concern ([EPA 2005](http://www.epa.gov/heatisld/resources/pdf/CoolPavesCompendium.pdf)).
* Use porous asphalt and open-graded friction courses in an integrated manner to enhance safety, provide positive drainage, and recharge groundwater (see [NAPA Porous Asphalt](http://www.hotmix.org/index.php?option=com_content&task=view&id=359&Itemid=863) website).

### Sustainable Asphalt Pavement End-of-Life

End-of-life strategies for asphalt pavements must assume that there will be no waste and that the entire pavement will be recycled. Depending on the existing structure and failure mechanism, the following alternatives are feasible:

* Remove the surface to create RAP for use in a new asphalt pavement. The underlying pavement layers can also be removed and processed for reuse as material for supporting layers or recycled in-place if deep sub-surface problems are not evident.
* The pavement surface and all or part of the underlying layers can undergo full-depth reclamation in which the surface is pulverized, optional stabilizer added, compacted, and capped with a new surface.
* A thick concrete overlay can be placed directly on top of an existing deteriorated asphalt pavement ([Harrington 2008](http://www.cptechcenter.org/publications/overlays/guide_concrete_overlays_2nd_ed.pdf)).

## Sustainable Practices for Concrete Pavements

Based on the factors previously described, the following are demonstrated practices that can be used to improve the sustainability of concrete pavements.

### Sustainable Concrete Pavement Design

As is true with asphalt pavements, the AASHTOware Pavement-METM mechanistic-empirical pavement design procedure combines key material properties with technologically advanced design computations to produce competent designs that are neither under- or over-designed (see [AASHTO Pavement-ME](http://www.aashtoware.org/Pages/DARWin-ME.aspx) website). The concrete design procedure is applicable to both jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP) constructed over a number of different supporting layers. The design procedure uses complex material characterization and modeling based on the actual concrete properties; this will allow the incorporation of various innovative concrete mixture designs that can reduce the emissions and energy consumption associated with the materials, while maximizing the use of local materials and those featuring high RIBMs content. Pavement thickness and joint design will also reflect the unique environmental conditions at the site, adding confidence that the design will meet the overall design objectives without waste.

In addition to the opportunities present through the use of Pavement-METM, specific design strategies that should be considered to improve concrete pavement sustainability include:

* Two-lift concrete pavement design that allows for the use of higher RIBMs content (recycled aggregate, SCMs) in the lower lift and wear resistant aggregate in the surface lift providing long-term skid resistance (see [CP Tech Center Two-Lift Concrete Paving](http://www.cptechcenter.org/projects/two-lift-paving/index.cfm) website).
* Precast concrete pavement systems that expedite construction and have the potential to optimize surface characteristics while reducing the environmental footprint (see [FHWA Highways for Life](http://www.fhwa.dot.gov/hfl/innovations/precast.cfm) website).
* Interlocking concrete pavers that can be used to create long-lasting, aesthetically appealing surfaces, especially for urban streets or heavily loaded facilities (see [Interlocking Concrete Pavement Institute](http://www.icpi.org/) website).
* Roller compacted concrete (RCC), a relatively low-energy, low-emission mixture, that can be placed as the final surface on low volume, low speed pavements, or on shoulders, or can be overlaid with asphalt or WMA to create a long-lasting, sustainable pavement (see [Portland Cement Association Roller-Compacted Concrete](http://www.cement.org/pavements/pv_rcc.asp) website). It is also used on heavily loaded pavements at ports and multi-modal facilities.
* Pervious concrete can be used for managing storm water runoff, filtration of pollutants, and recharge groundwater supplies.

### Sustainable Concrete Pavement Material Selection and Construction

For concrete pavements, the vast majority of the energy and emissions associated with the materials is from the production of the portland cement ([Van Dam and Taylor 2009](http://www.cproadmap.org/publications/sustainability_briefing.pdf)). As such, the key to reducing the environmental footprint of concrete is to reduce the amount of portland cement used in the pavement. There are three broad strategies to accomplish this:

* Use less concrete thickness. Through proper pavement design and the selection of a concrete mixture with appropriate properties, the slab thickness may be reduced. For example, Pavement-METM recognizes that a thinner concrete slab is required if the concrete has a low coefficient of thermal expansion (CTE) versus a higher CTE, all other variables held constant. Similarly, for a given CTE, Pavement-METM will recommend a thinner slab if a shorter transverse joint spacing is employed. Less concrete may also be required if precast concrete pavement systems, prestressed pavement systems, or interlocking concrete pavers are used, potentially having overall positive effects on sustainability.
* Use less hydraulic cement. It is increasingly common to reduce the amount of hydraulic cement added to a concrete mixture, replacing it with blended cements, geopolymer cements and/or an SCM such as slag cement and/or fly ash. This replacement can be done at the concrete plant or by the cement manufacturers who offer blended cements for multiple applications ([Van Dam and Smith 2011](http://www.fhwa.dot.gov/pavement/concrete/pubs/hif11025/hif11025.pdf)). Since SCMs are often derived from the waste stream of other industries, this replacement can significantly reduce the energy and carbon footprint of the concrete while at the same time making it more economical and durable. Thus, the replacement of portland cement with SCMs is an exceptional example of a readily implementable sustainable practice ([Van Dam and Taylor 2009](http://www.cproadmap.org/publications/sustainability_briefing.pdf)). Further reductions in environmental impact can be realized through the use of portland-limestone cements, which have been shown to have excellent performance (Thomas et al. 2010; Van Dam, Smartz, and Laker 2010; [Van Dam and Smith 2011](http://www.fhwa.dot.gov/pavement/concrete/pubs/hif11025/hif11025.pdf)).
* Use less cementitious materials in the concrete. Through the use of aggregate grading optimization, the cementitious content of concrete can be reduced while at the same time improving the fresh and hardened properties of the concrete ([Taylor et al. 2006](http://www.cptechcenter.org/publications/imcp/index.cfm)). This reduces the life cycle energy and carbon footprint of the concrete while providing economic savings.

In addition to reducing the amount of portland cement in the concrete, aggregate choices can also have a large impact on sustainability. RIBMs such as RCA and air-cooled blast furnace slag have been used as aggregate in concrete paving mixtures.

As is true with asphalt materials, regardless of the materials choices made, transporting “sustainable” materials great distances by trucks will have negative economic and environmental impacts. Thus the environmental impact of transporting materials must be considered in the decision-making process.

### Sustainable Concrete Pavement Maintenance and Rehabilitation

Numerous maintenance and rehabilitation strategies are available to keep concrete pavements in good serviceable condition. Strategies that can have the greatest positive impact on sustainability are those that 1) maintain smoothness and surface friction while minimally disrupting traffic operations, and 2) use the least amount of non-renewable, high-energy, high-emission materials. The following are example strategies that meet those requirements:

* Pavement preservation and repair strategies– these include a number of non-structural treatments designed to keep good pavements in good condition. Inherently such treatments require only short lane closure times or can use moving lane closure operations. Applicable treatments include partial- and full-depth repair, dowel bar retrofitting, slab stabilization, edgedrain cleaning and repair, and diamond grinding (see [Pavement Preservation](http://www.pavementpreservation.org/) website). Diamond grinding can be applied multiple times over the life of a concrete pavement, and is exceptionally effective in reducing roughness, restoring surfacing friction, and reducing noise emissions. The technique can be applied with little disruption to traffic, generates minimal waste, and does not require additional non-renewable materials.
* Various overlay options are available to rehabilitate concrete pavements that cannot be effectively treated through preservation and repair. In the past, the most common approach was to place an asphalt overlay on an existing concrete pavement, but the joints and distress in the underlying concrete have a tendency to quickly reflect through the overlay, resulting in reduced serviceability and premature failures that compromise sustainability. A recently completed study found that the life of an asphalt overlay was often not used optimally, and thus significant life cycle environmental impacts were incurred ([Ram et al. 2011](http://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC1550_354975_7.pdf)). Alternatively, concrete overlays have been found to be effective in rehabilitating existing concrete pavements ([Harrington 2008](http://www.cptechcenter.org/publications/overlays/guide_concrete_overlays_2nd_ed.pdf)).

### Sustainable Concrete Pavements In-Service

As is true with asphalt pavements, upwards of 90 percent of the energy and emissions associated with a pavement are incurred due to the operation of vehicles during its service life. Furthermore, the pavement’s interaction with the surrounding community and environment also affect the quality of life and health of ecosystems. Examples of methods that can be used to improve the sustainability of in-service concrete pavements include the following:

* Construct and maintain concrete pavements in a smooth condition; vehicles operating on smooth pavements have reduced operating costs, improved fuel efficiency, and reduced emissions. Diamond grinding has been found to be a very effective treatment for restoring smoothness to rough concrete pavements.
* Construct and maintain quieter pavement surfaces that will minimize the impact on the surrounding community ([Rasmussen, Sohaney, and Wiegand 2011](http://www.cptechcenter.org/publications/surface_char_specs_tech_brief.pdf)). This is particularly important for high-speed facilities in urban areas but has value even in rural areas.
* Use patterned and/or colored concrete or interlocking concrete pavers to creating aesthetically pleasing pavements that can be clearly demarcated for various uses (e.g., traffic lanes, pedestrian crosswalks, bike lanes, and so on). This is most important in urban areas.
* Use pervious concrete in an integrated manner to enhance safety, reduce noise, provide positive drainage, and recharge groundwater supplies (see [Pervious Concrete](http://www.perviouspavement.org/) website).
* Where Urban Heat Island Effect may be an issue, consider using pavement or other strategies which reduce or mitigate the heat absorption. Another option is to use light colored concrete (e.g., addition of titanium dioxide) ([EPA 2005](http://www.epa.gov/heatisld/resources/pdf/CoolPavesCompendium.pdf)). Also consider the use of interlocking concrete pavers treated with photocatalytic titanium dioxide or two-lift pavements with photocatalytic titanium included in the top lift; these will remain highly reflective and have the ability to mitigate harmful emissions. The use of lighter colored pavements can also help improve nighttime visibility and reduce lighting requirements, thereby saving both money and energy ([EPA 2009](http://epa.gov/hiri/mitigation/pavements.htm)). In some environments, there can be too much reflection and some discomfort from too much heat reflection during the day.

### Sustainable Concrete Pavements End-of-Life

End-of-life strategies for concrete pavements must assume that there will be no waste and that the entire pavement will be recycled. The following alternatives are generally feasible:

* Fracture, transport, and crush the concrete to create RCA for use in new concrete, base, or subbase (ACPA 2009). Alternatively, fractured concrete can be used in large pieces as rip rap or erosion protection. Underlying layers can also be removed and processed for reuse as material for supporting layers or recycled in-place if deep sub-surface problems are not evident.
* The concrete surface can be fractured and crushed in-place using mobile crushers, and used as base or subbase for the new pavement. This eliminates the need for transporting the concrete off-site for processing.
* An unbonded concrete overlay can be placed on top of a deteriorated concrete pavement using an effective bondbreaker to separate the two ([Harrington 2008](http://www.cptechcenter.org/publications/overlays/guide_concrete_overlays_2nd_ed.pdf)).
* The existing concrete pavement can be rubblized, and then overlaid with a thick asphalt layer (NAPA 2006).

## Assessment of Sustainable Practices

The assessment of sustainable pavement practices is an area of immense interest, and numerous research and implementation activities are currently underway. As previously discussed, it is generally agreed that economic needs must be assessed using a rigorous LCCA procedure. To address the environmental and societal needs, a number of pavement sustainability rating systems are currently under development or refinement, and research continues to establish an implementable model for conducting pavement environmental life cycle assessment (ELCA). In addition, [Zietsman et al. (2011)](http://www.camsys.com/pubs/nchrp_rpt_708.pdf) provide a general discussion on the development of sustainability performance measures. This section will briefly discuss pavement rating systems and introduce ELCA.

### Environmental Life Cycle Assessment (ELCA)

ELCA, also known simply as life cycle assessment (LCA), provides an environmental assessment of a product over its life cycle: from the first stages of acquiring raw materials (whether harvested or extracted) to transporting and ultimate processing of these raw materials into a product (such as a pavement), to the use of the product, and ultimately to the recycling or disposal of the product. An ELCA accomplishes this by accounting for environmental impact in terms of mass or energy flows in and out of a set boundary, calculating waste and emissions generated during the entire life-cycle of the product.

Sustainable pavement rating systems often focus on a small set of criteria (e.g., recycled content, carbon footprint) or a given phase of a pavement’s life (e.g., material acquisition, construction), both of which provide only a partial snapshot of the pavement’s environmental impact. An ELCA uses detailed environmental data and scientifically derived models to evaluate the environmental impact of the pavement over its entire life. As a result, an ELCA of a pavement can include specific environmental effects due to:

* Extraction of materials and fuel used for energy.
* Manufacturing of components.
* Transportation of materials and components.
* Material processing and construction.
* Operations, including maintenance and repair.
* Demolition, disposal, recycling, and reuse of the pavement at the end of its functional or useful life.

An ELCA can evaluate a full set of environmental impacts and indicators including, among other things, land use, resource use, climate change, health effects, acidification, and toxicity.

A limiting factor in the widespread implementation of ELCA for pavement evaluation is that it involves a time-consuming manipulation of large quantities of data and uses sophisticated software, both of which are often proprietary. Furthermore, the source, validity, and legitimacy of the data are not always well known or well documented, hampering the ability to accurately apply ELCA to a given project. And, although a scientific basis exists for the environmental impact models, there are always questions regarding their accuracy.

As a result of the complexity and expense of running an ELCA, it is not commonly done at this time. It is likely that simplified ELCA tools such as [PaLATE](http://www.ce.berkeley.edu/~horvath/palate.html) will continue to develop and provide useful input with regards to life cycle environmental impact.

### Sustainable Pavements Rating Systems

An example of a sustainable pavement rating system designed for general adoption is called [GreenroadsTM](http://www.greenroads.us/). [GreenroadsTM](http://www.greenroads.us/) focuses exclusively on measuring performance of sustainable roadway design and construction, and remains under development. It is available in an implementable form, with the current version identified as Version 1.5 ([Muench et al. 2011](http://www.greenroads.us/14/manual.html)). The [GreenroadsTM](http://www.greenroads.us/) system attempts to quantify the sustainable attributes of a roadway project with the stated purpose of:

* Defining project attributes that contribute to roadway sustainability.
* Accounting for sustainability-related activities.
* Communicating sustainable project attributes.
* Managing and improving roadway sustainability.
* Certifying projects.

The [GreenroadsTM](http://www.greenroads.us/) system recognizes two major best-practice categories: mandatory (Project Requirements) and voluntary (Voluntary Credits). Mandatory best practices provide the minimum level of sustainable activities and each must be met within a project for it to be considered in the Greenroads TM system. These focus on environmental and economic decision-making, public engagement, design for long-term performance, construction planning, and planning for lifetime monitoring and maintenance. The voluntary practices are optional attributes for which credits are given. In total, there are currently 37 Voluntary Credits in which up to 108 points may be given. In addition, up to 10 “Custom Credits” can be awarded for a total of 118 available points. The mandatory and voluntary practices and the assigning of credits and points are described in detail in the *Greenroads TM Manual v1.5* ([Muench et al. 2011](http://www.greenroads.us/14/manual.html)).

For a project to be evaluated and certified as a “greenroad,” the project team overseeing the work documents how the Project Requirements were met and which Voluntary Credits were pursued. This information is submitted and the Greenroads TM team verifies the application and tallies the points earned, assigning a certification level in accordance with Table 13-1.

Table 13-1. The four certification levels within GreenroadsTM ([Muench et al. 2011](http://www.greenroads.us/14/manual.html)).

| **Certification Level** | **Project Requirements** | **Voluntary Credits** |
| --- | --- | --- |
| Certified | All | 32 – 42 |
| Silver | All | 43 – 53 |
| Gold | All | 54 – 63 |
| Evergreen | All | 64 and greater |

### FHWA Sustainable Highways Self-Evaluation Tool ([INVEST](http://www.sustainablehighways.org/))

Members of the Greenroads TM team were contracted by the FHWA to develop the [Sustainable Highways Self-Evaluation Tool](http://www.sustainablehighways.org/) website). Also know as [INVEST](http://www.sustainablehighways.org/) (for Infrastructure Voluntary Evaluation Sustainability Tool), the current Pilot Version (released on April 22, 2011) represents a significant revision from the originally released Beta Version (released Fall 2010). The Pilot Version focuses exclusively on the evaluation of specific projects through the Project Development (PD) credits, and the System Planning and Operations and Maintenance credits are currently being revised for later release ([Anderson, Muench, and Seskin 2011](http://www.sustainablehighways.org/)).

[INVEST](http://www.sustainablehighways.org/) is a point based system in which 30 separate PD credits are designed to identify characteristics of sustainable highways and provide information and techniques to help integrate best sustainability practices into highway and roadway projects. Figure 13-3 provides a list of the credits and which triple-bottom line principles are addressed by each. It is specifically stated that [INVEST](http://www.sustainablehighways.org/) in not a requirement nor is it intended to encourage comparisons across transportation agencies and projects.

## Concluding Remarks on Pavement Sustainability

Sustainability is of increasing interest to transportation agencies that are recognizing the importance of considering the triple-bottom line of economic, environmental, and social impacts in the decision-making process. Sustainable pavements are those in which the triple-bottom line is considered over all phases of the life cycle, from design, material acquisition and processing, construction, operation, maintenance and rehabilitation, and through the end of life. Features of a sustainable pavement include:

* A long-term perspective reflected in an analysis period that is typically 50 years or possibly longer.
* Economic costs are considered over the entire analysis period using an LCCA that evaluates both agency costs and user costs, and a sensitivity analysis to determine the significance of the various inputs.
* A pavement design that meets specific project needs and is sensitive to the context of where the pavement is placed, including environmentally sensitive areas like wetlands as well as urban versus rural locations.
* The selection of materials that reduces environmental footprint and energy consumption over the life cycle by maximizing the use of RIBMs and local materials and reduces the cost and environmental damage associated with transporting materials long distances.
* The application of maintenance and rehabilitation activities that restore serviceability while minimizing traffic disruption and the use of non-renewable resources.
* The maintenance of in-service pavements that are safe, smooth, and quiet, and that also possess other features that meet the needs of the user, the surrounding community, and natural environment.
* At the end of life, the pavement must be completely recycled. However, this may not always be possible and should be accounted for during the LCA.



Figure 13-3. [INVEST](http://www.sustainablehighways.org/) credit comparison chart including which triple-bottom line principles are addressed by each credit ([Anderson, Muench, Seskin 2011](http://www.sustainablehighways.org/)).

The ease and efficiency of recycling old asphalt pavements into new pavements is one of the most outstanding features with regards to increasing pavement sustainability. Further, a number of other RIBMs can be used in new asphalt mixtures (i.e. GTR, RAS, recycled aggregates) that further increase the sustainability of this material. The recent introduction of WMA technologies offers another opportunity to reduce the energy and emissions associated with asphalt pavement construction. And combining these materials with perpetual pavement design offers some additional opportunities to enhance longevity while incorporating various environmental enhancements including the use of high RAP mixtures in some layers, WMA technology, and the ability to maintain and rehabilitate the perpetual pavements with minimal traffic disruption.

The longevity of concrete pavements is one attribute that contributes to their overall sustainability. Through proper design and preservation—including periodic diamond grinding to maintain a safe, smooth, and quiet surface— concrete pavements can achieve service lives of 50 years or more. Further improvements in sustainability focus on reducing the amount of portland cement used through good pavement design, optimized aggregate grading, and the proper use of SCMs and/or blended cements. The use of lightweight aggregate in the fine fraction provides a constant source of water for long term hydration and strength gain. Alternative design practices, including two-lift construction, precast concrete pavement systems, interlocking concrete pavers, pervious concrete, titanium dioxide and RCC, all can play a role in improving sustainability. And concrete’s ability to be easily molded, patterned, and colored makes it a great choice for sustainable pavements in an urban environment.

As sustainability increases in importance, transportation agencies are seeking tools to assess the sustainability of their pavements. [GreenroadsTM](http://www.greenroads.us/) and the FHWA’s [INVEST](http://www.sustainablehighways.org/) are two pavement sustainability rating systems designed for broad distribution that are currently under evaluation. Sophisticated ELCA tools that can assess environmental impact over the life cycle are available, but performing these analyses are time consuming and require the use of extensive data and complex software, both of which are often proprietary.

## References

American Concrete Pavement Association (ACPA). 2009. *Recycling Concrete Pavements.* EB043P. American Concrete Pavement Association, Skokie, IL. ISBN 978-0-9800251-1-8

American Society of Civil Engineers (ASCE). 2007. *The Vision for Civil Engineering in 2025*. Based on The Summit on the Future of Civil Engineering—2025 held June 21–22, 2006. American Society of Civil Engineers, Reston, VA.

American Society of Civil Engineers (ASCE). 2009. “Board of Direction Views Sustainability Strategy as Key Priority.” *ASCE News.*  Vol. 34, No. 1.

Anderson, J., S. Muench, and S. Seskin. 2011. *Sustainable Highways Self-Evaluation Tool.*  Pilot Test Version. Compendium of Credits. Federal Highway Administration. United States Department of Transportation, Washington, DC. Available online at: <http://www.sustainablehighways.org/>.

Bentsen, R. 2010. *Illinois Tollway Authority Jump Starts Asphalt Shingle Recycling in the State*. Construction Materials Recycling Association (CMRA). Available online at: <http://www.cdworldmag.com/index.php/features/161-illinois-tollway-authority-jump-starts-asphalt-shingle-recycling-in-the-state.html>.

Environmental Protection Agency (EPA). 2011. *Ground Rubber Applications.* Available online at: <http://www.epa.gov/osw/conserve/materials/tires/ground.htm>.

Environmental Protection Agency (EPA). 2009. “Heat Island Effects.” Website. Environmental Protection Agency, Washington, DC. <http://epa.gov/hiri/mitigation/pavements.htm>.

Environmental Protection Agency (EPA). 2005. *Reducing Urban Heat Islands: Compendium of Strategies – Cool Pavements*. Draft Report. Environmental Protection Agency, Washington, DC. Available online at: <http://www.epa.gov/heatisld/resources/pdf/CoolPavesCompendium.pdf>.

Federal Highway Administration (FHWA). 2011a. *Life-Cycle Cost Analysis Software*. Federal Highway Administration, Washington, DC. Available online at: <http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm>.

Federal Highway Administration (FHWA). 2011b. *The Role of FHWA Programs in Livability: State of the Practice Summary.* Federal Highway Administration, Washington, DC. Available online at: <http://www.fhwa.dot.gov/livability/state_of_the_practice_summary/research2011.pdf>.

Harrington, D. 2008. *Guide to Concrete Overlays – Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements.* ACPA Publication TB021.02P. National Concrete Pavement Technology Center, Iowa State University, Ames, IA. Available online at: <http://www.cptechcenter.org/publications/overlays/guide_concrete_overlays_2nd_ed.pdf>.

McDonough, W. and M. Braungart. 2002. *Cradle to Cradle: Remaking the Way We Make Things.*  North Point Press, New York, New York. ISBN 0-86547-587-3.

Muench, S. T., J. L. Anderson, J. P. Hatfield, J. R. Koester, and M. Söderlund. 2011. *Greenroads Manual v1.5.* (J. L. Anderson, C. D. Weiland, and S. T. Muench, Eds). University of Washington, Seattle, WA. Available online at: <http://www.greenroads.us/14/manual.html>.

National Asphalt Paving Association (NAPA). 2006. *Rubblization*. Information Series 132. National Asphalt Paving Association, Lanham, MA.

National Asphalt Paving Association (NAPA). 2009. *Black and Green: Sustainable Asphalt, Now and Tomorrow.* Special Report Number 200. National Asphalt Paving Association, Lanham, MA. Available online at: <http://www.hotmix.org/images/stories/sustainability_report_2009.pdf>.

Newcomb, D. E. 2009. *Thin Asphalt Overlays for Pavement Preservation.* Information Series Number 200. National Asphalt Paving Association, Lanham, MA. Available online at: <http://www.hotmix.org/images/stories/is-135.pdf>.

Ram, P., T. Van Dam, J. Meijer, and K. Smith. 2011. *Sustainable Recycled Materials for Concrete Pavements.*  RC-1550. Michigan Department of Transportation, Lansing, MI. Available online at: <http://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC1550_354975_7.pdf>.

Rasmussen, R. O., R. Sohaney, and P. Wiegand. 2011. *Concrete Pavement Specifications for Reducing Tire-Pavement Noise.*  Tech Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA. Available online at: <http://www.cptechcenter.org/publications/surface_char_specs_tech_brief.pdf>.

Senge, P., B. Smith, N. Kruschwitz, J. Laur, and S. Schley. 2008. *The Necessary Revolution: How Individuals and Organizations Are Working Together to Create a Sustainable World.* Doubleday, NY. ISBN: 978-0-385-51901-4.

Taylor, P. C., S. H. Kosmatka, G. F. Voigt, et al. 2006. *Intergrated Materials and Construction Practices for Concrete Pavements: A State-of-the-Practice Manual*. FHWA-HIF-07-004. Federal Highway Administration, Washington, DC. Available online at: <http://www.cptechcenter.org/publications/imcp/index.cfm>.

Thomas, M. D., A., D. Hooton, K. Cail, B. A. Smith, J. De Wal, and K. G. Kazanis. 2010. “Concrete Produced With Portland Limestone Cement.” *Concrete International 32*(1). American Concrete Institute, Farmington Hills, MI.

Van Dam, T. and K. Smith. 2011. *ACPT Tech Brief: Blended and Performance Cements*. FHWA-HIF-11-025. Federal Highway Administration, Washington, DC. Available online at: <http://www.fhwa.dot.gov/pavement/concrete/pubs/hif11025/hif11025.pdf>.

Van Dam, T., and P. Taylor. 2009. *Building Sustainable Pavements with Concrete.* National Concrete Pavement Technology Center. Iowa State University. Ames, IA. 39 pp. <http://www.cproadmap.org/publications/sustainability_briefing.pdf>.

Van Dam, T., B. W. Smartz, and T. S. Laker. 2010. “Use of Performance Cements (ASTM C1157) in Colorado and Utah: Laboratory Durability Testing and Case Studies.” *International Conference on Sustainable Concrete Pavements: Practices, Challenges, and Directions*. Federal Highway Administration, Washington, DC.

World Commission on Environment and Development (WCED). 1987. *Our Common Future: The Report of the World Commission on Environment and Development.* World Commission on the Environment and Development. United Nations, New York. Oxford University Press. [ISBN 0-19-282080-X](http://en.wikipedia.org/wiki/Special%3ABookSources/019282080X).

Zietsman, J., T. Ramani, J. Potter, V. Reeder, and J. DeFlorio. 2011. *A Guidebook for Sustainability Performance Measurement for Transportation Agencies.* NCHRP Report 708. Transportation Research Board, Washington, DC. Available online at: <http://www.camsys.com/pubs/nchrp_rpt_708.pdf>.