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BUILDING SUSTAINABLE PAVEMENTS WITH CONCRETE

BRIEFING DOCUMENT

CP ROAD MAP
shaping the future of concrete pavement

Track 13: Concrete Pavement Sustainability

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ABOUT THIS DOCUMENT

This document is an initial product of the Sustainability Track (Track 13) of the Long-Term Plan for Concrete Pavement Research and Technology (CP Road Map). The CP Road Map is a national research plan jointly developed and implemented by the concrete pavement stakeholder community, including Federal Highway Administration, academic institutions, state departments of transportation, and concrete-pavement–related industries.

Coordinators of the Sustainability Track are Peter Taylor, Associate Director, National Concrete Pavement Technology Center, Iowa State University; and Dale Harrington, Snyder & Associates. The primary technical expert is Tom Van Dam, Program Manager, Applied Pavement Technology. CP Road Map publications and other operations support services are provided by the National Concrete Pavement Technology Center, Iowa State University.

For details about the CP Road Map, see www.cproadmap.org/index.cfm.

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Track 13:
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INTRODUCTION

It is becoming increasingly apparent that some human activities and development practices are negatively affecting the well-being of the planet and putting future generations at risk. Public agencies are recognizing the paramount importance of adopting more "sustainable" practices and products—those that preserve or enhance economic, environmental, and social well-being—in designing, constructing, and maintaining public infrastructure, including pavements.

We do not inherit the earth from our ancestors, we borrow it from our children.

– Native American proverb

Owners of the nation's roadway system are beginning to consider imposing sustainability measures in their contracts. This is an important step toward a more sustainable infrastructure. But pavement owners, designers, material suppliers, and contractors are handicapped by two features of the paving community: (1) the lack of practical information about pavement sustainability and (2) the many other critical needs that compete with sustainability for attention and resources.

1. **Lack of practical information**. Little straightforward information is available that clearly explains what sustainability means. Pavement owners and managers need guidance about the benefits of including sustainability in their decision-making processes, and tools to assist them in that process. They also need practical guidance about implementing current products and practices in ways that enhance pavement sustainability.

2. **Competing needs**. Street and road agencies must balance the increasing necessity to implement sustainable pavement solutions with many other critical challenges. Pavements are aging and deteriorating; one-third of the pavement system, about 1.3 million miles, is in poor condition or worse and has earned a grade of D- in the recently released American Society of Civil Engineers report card (ASCE 2009A). Traffic volumes and vehicle loads continue to increase, stressing already deteriorating pavements and, in major metropolitan areas, resulting in serious congestion problems. Year after year, roadway budgets fall far short of meeting these critical needs; the annual shortage is estimated at $115.7 billion. These needs and costs must be balanced with the costs of improving pavement sustainability, which as yet is unquantifiable.

This document can help. Its purpose is to make sustainability concepts and practices accessible to the concrete pavement community, in order to effect positive economic, environmental, and social change. The good news in brief: Many intrinsic characteristics of concrete make it a relatively sustainable material for pavements. Many concrete-based solutions for new and existing pavements have elements that may improve the sustainability of a pavement system. Moreover, implementing sustainable pavement solutions helps owner agencies address their pavement performance and budget challenges, because cost-effectiveness and high performance are integral characteristics of sustainable solutions.

Following is a brief overview of this document:

1. The document begins with a basic definition of sustainability. This section also describes characteristics of concrete that may be considered sustainable.

2. The next section explains why it is important for all stakeholders in the concrete pavement industry to focus on enhancing pavement sustainability.

3. The document then introduces seven common-sense principles for adopting sustainable concrete pavement solutions. This discussion emphasizes that, although sustainability issues are complex and present problems needing research, solutions are often based on common sense.

4. The document then presents approaches to quantify sustainability factors. This section describes research needed to develop sophisticated analysis tools for measuring, evaluating, and comparing the effects of various pavement solutions on sustainability.

5. Finally, the document discusses pavement sustainability research that is being addressed through the Sustainability Track of the Long-Term Plan for Concrete Pavement Research and Technology (CP Road Map). The CP Road Map is a national stakeholder-developed research plan for developing pavement innovations for the 21st century.

Due to the dynamic nature of the topic, this document is a “living” resourc**e** for concrete pavement stakeholders. It will be revised and updated regularly to reflect an evolving understanding of pavement sustainability issues, new research-based best practices for enhancing concrete pavement sustainability, and additional issues identified for investigation.

Currently, for example, this document does not provide numerical data that agencies can use to compare the sustainability of various pavements or pavement treatments. Industry is beginning to provide some basic data (ACPA 2007). As tools for making such comparisons become available, this document will be updated to describe them.

WHAT IS SUSTAINABILITY?

The word “sustainability” is used frequently, especially in connection with public policy. But what does it mean, particularly in terms of pavements?

A basic definition of sustainability is the capacity to maintain a process or state of being into perpetuity. In the context of human activity, sustainability has been described 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).

Under this characterization, three general categories of needs and/or impacts are generally considered: environmental needs/impacts, economic needs/impacts, and social needs/impacts. Together, the three categories form a “triple bottom line” (Elkington 1994) of sustainability. That is, no category is undervalued; instead, a workable balance among the three is found. This concept can be expressed graphically, as shown in figure 1.

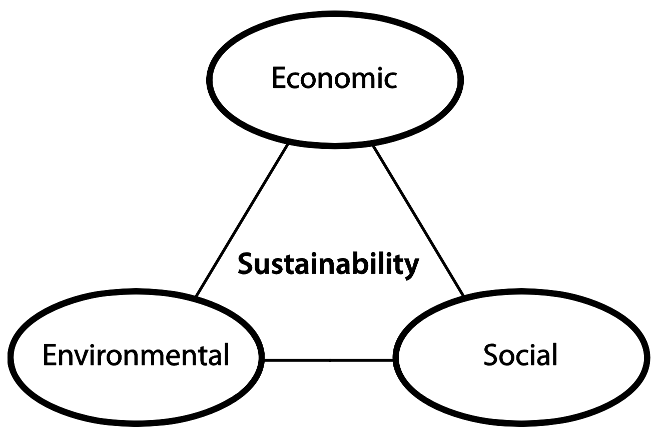


Figure 1. Representation of sustainability’s “triple-bottom line”

In any activity, including pavement construction and maintenance, the three considerations often compete. For example, constructing narrower rather than wider pavement lanes may reduce the owner-agency’s construction costs (meeting an economic need) and may reduce the pavement’s impact on the surrounding natural ecosystem (meeting an environmental need). However, narrower lanes may be associated with higher crash rates (increasing both social and economic costs). Sustainable solutions are those that seek out win-win-win scenarios in which all three considerations are balanced.

Balancing considerations means identifying appropriate, measurable factors in all three categories, collecting data and applying tools to quantify the impact of each factor, and assessing the combined impacts of the factors.

Complicating this quantifying process is that factors must be evaluated throughout a pavement's life—during design, materials processing, construction, operations, preservation/rehabilitation, and reconstruction/recycling.

Further, each category of sustainability is measured or rated in different terms: economic factors in terms of dollars, environmental factors in terms of global warming and/or air and water quality, and social factors in terms yet to be determined. There is no obvious way to balance or weigh these different factors. Fully assessing the sustainability of a project requires a sophisticated analysis of current and detailed data reflecting at least three different terms of measurement. Such an analysis is beyond the current state of the practice.

Fortunately, concrete pavement stakeholders do not have to wait for sophisticated data collection and analysis tools to develop sustainable pavements. Many characteristics of concrete and many current practices related to concrete pavement can be used to enhance pavement sustainability. For example, concrete pavements have the following characteristics:

- Have long life (generally, 30 years or more) and do not often need to be reconstructed.
- Are smooth, quiet (down to 98 dB [Rasmussen et al. 2008]), and safe.
- Offer low rolling friction to vehicles, reducing fuel consumption (Athena 2009).
- Have a light-colored surface, providing good visibility and reducing roadway lighting requirements.
- Can recycle significant amounts of industrial residuals and other recycled materials in their construction and so reduce the use of non-renewable resources.
- Are themselves recyclable.
- Can be constructed quickly and efficiently.
- Are cost effective to construct and, with their long design lives, have relatively low life-cycle costs.
- Once constructed, have a limited impact on the surrounding environment.
- Are community friendly, with aesthetically pleasing, reflective surfaces that minimize urban heat.

As indicated in the list above, strategies are already being implemented that enhance pavement sustainability—that is, that make a pavement more cost-effective, environmentally friendly, and serviceable for social needs throughout its life.

Some strategies that have been part of standard practice for more than 100 years have resulted in long-lasting and cost-effective concrete pavements.

Other strategies, especially those that focus on enhancing concrete pavement's environmental and community friendliness, are still in the initial phase of development.

Bottom line: Stakeholders can implement, today, many concrete solutions that enhance pavement sustainability.

WHY IS PAVEMENT SUSTAINABILITY CRITICAL?

Before strategies for increasing concrete pavement sustainability can be considered, it is necessary to consider why sustainability is important to stakeholders.

First, sustainability in concrete pavements is simply good engineering, which always involves working with limited resources to achieve the best product possible. What has changed is the way the product is evaluated and the period of time over which it is evaluated. Whereas in the past economic factors were paramount for evaluation, now sustainability requires that environmental and social factors be considered as well.

Further, the analysis includes the entire life cycle of the project and encompasses all impacts (both positive and negative) from the point of inception to the end of life, as shown in figure 2. This type of system-wide analysis is often referred to as a "cradle-to-grave"—or, more appropriately, a "cradle-to-cradle"—analysis (McDonough and Braungart 2002).

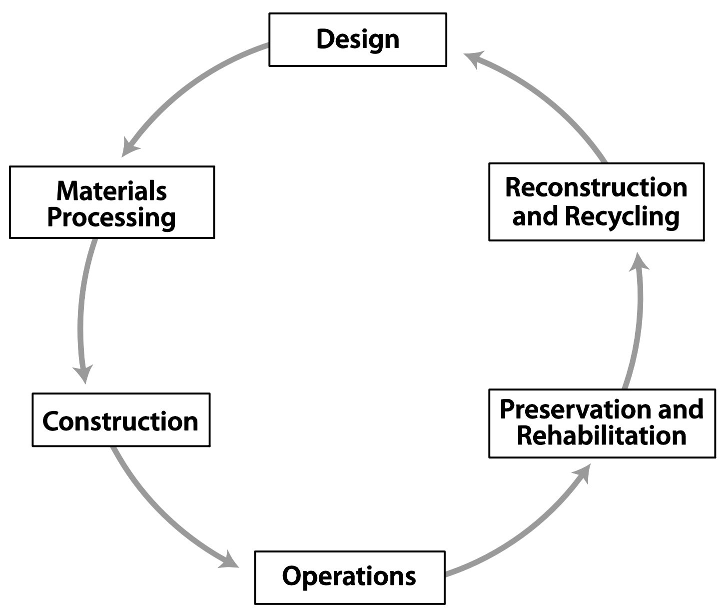


Figure 2. The concept of "good" pavement engineering must expand to cradle-to-cradle, life-cycle performance

Although most civil engineers consider this a challenging prospect, many may also find it engaging.

It is important to remember that sustainability is not about perfection. It is about balancing competing and often contradictory interests and making incremental improvements as our knowledge improves.

Second, sustainability is increasingly being demanded by the public. The American Society of Civil Engineers (ASCE) Board of Direction recently approved the following acknowledgment of the need for civil engineers to adapt their roles to meet public expectations regarding sustainability (ASCE 2009B):

> The public's growing awareness that it is possible to achieve a sustainable built environment while addressing such challenges as natural and man-made disasters, adaptation to climate change, and global water supply is reinforcing the civil engineer's changing role from designer/constructor to policy leader and life-cycle planner, designer, constructor, operator, and maintainer (sustainer).

A similar belief is clearly enunciated in a vision statement adopted at the 2006 Summit on the Future of Civil Engineering—2025, which notes that civil engineers are "entrusted by society to create a sustainable world and enhance the global quality of life" (ASCE 2007). This aspiration reflects the responsibility of those charged with providing public infrastructure, including concrete pavements.

Third, emphasizing sustainability provides opportunities for the concrete pavement community to discuss concrete's benefits as a paving material. Because of its versatility, cost-effectiveness, local availability, and longevity, concrete is the most commonly used building material on the planet. Modern civilization is built on concrete. Concrete's ubiquity, however, results in a relatively large environmental footprint (or impact), which may be negatively perceived. In the dialog about sustainability, concrete's advocates can point out that properly constructed concrete pavements have less environmental impact than pavements built with other materials. (Wathne 2008)

A fourth advantage of adopting a focus on sustainability is that the concrete pavement industry can become more attractive to a younger, more environmentally and socially motivated workforce. According to the *Jobs Rated Almanac*, "civil engineer" was the lowest-ranked engineering profession (70th out of a total of 250 jobs), and "construction worker" was ranked 247 out of 250, between "cowboy" and "fisherman" (Krantz 2002).

“[M]any young people interested in promoting environmental and social issues may perceive civil engineers as part of the problem, not the solution.”

As ASCE recognizes, many young people interested in promoting environmental and social issues may perceive civil engineers as part of the problem, not the solution. The final sentence in the ASCE Board of Direction’s sustainability statement (mentioned above) observes that “[c]ivil engineers are not perceived to be significant contributors to a sustainable world” (ASCE 2009B). In *The Necessary Revolution: How Individuals and Organizations are Working Together to Create a Sustainable World*, Senge et al. (2008) quote a number of authoritative business sources who believe that employees are making career choices based on a company’s commitment to sustainability.

One source argues, “The best people want to do work that contributes to society with a company whose values they share . . . .” (Jeroen van der Veer, Royal Dutch Shell), and another source explains, “It’s a powerful motivator, particularly for younger employees today, to know your company is working in the right areas and doing the right things . . . .” (Paul Tebo, formerly of Dupont).

In this environment, the pavement industry can change negative perceptions and attract the young talent needed for the future by advancing sustainability of concrete pavements.

And finally, focusing on sustainability will make the concrete pavement industry more innovative and more competitive. This change can already be observed through the increasing emphasis on such diverse innovations as in-place recycling of existing concrete pavement, two-lift construction, safe and quiet surfaces, pervious concrete, optimized gradations that reduce cementitious content, and concrete with higher percentages of supplementary cementitious material (SCM), to name a few. Each of these examples clearly demonstrates win-win-win scenarios having positive economic, environmental, and social impacts.

“ ‘. . . [P]eople want to do work that contributes to society . . .’ ”

Emerging concrete technologies and techniques that are poised to bring even more dramatic positive changes include photocatalytic cements to treat air pollution, carbon sequestering cements and aggregates, further increases in SCM content, embedded sensing technologies for construction and infrastructure health monitoring, and advanced construction processes that minimize energy use and emissions.

The industry’s challenge is to step out of the box and, rather than focus exclusively on simply meeting existing specifications, re-imagine what a concrete pavement can be and work with the various stakeholders to further increase the economic, environmental, and social benefits inherent in concrete pavements.

COMMON-SENSE PRINCIPLES REGARDING SUSTAINABILITY

To approach concrete pavement sustainability in a practical fashion, it is necessary to link sustainability to familiar concepts in the pavement construction community. The following seven common-sense principles can help make this link:

- Principle 1: Get Smart
- Principle 2: Design to Serve the Community
- Principle 3: Choose What You Use
- Principle 4: Less is More
- Principle 5: Minimize Negative Impact
- Principle 6: Take Care of What You Have
- Principle 7: Innovate

Each of these principles is discussed in the following sections, along with practical suggestions for employing the principles. It is important to consider each principle not only on its own merits but also in terms of its interdependency with, and/or potential competition with, other principles.

Principle 1: Get Smart

This is an exhortation not to be content with the status quo. It is a call to educate yourself and staff about making concrete pavements an integral part of sustainable infrastructure. Although it will require some formal training, education should not be restricted to traditional learning. It should be integrated with day-to-day operations. Support continuing education and innovative thinking. Find information about new innovations described in a new series of Moving Advancements into Practice (MAP) Briefs (/www.cproadmap.org/publications/MAPbrief7-1.pdf). Follow sustainability-related research being conducted through a national plan, which is summarized at the end of this document.

“Getting smart includes embracing the concept of pavement life cycle.”

Much of this educational process needs to occur long before design and construction are initiated. Getting smart includes embracing the concept of the pavement life cycle. Various processes affect pavement sustainability during each stage of its life—design, materials processing, construction, operations, preservation/ rehabilitation, and reconstruction/recycling. The effects of these processes must be clearly understood, so that processes can be appropriately applied. Clearly, this is a complicated and emerging science, but all of us can appreciate the interconnectivity of all life cycle stages.

Specific actions that can be taken include the following:

- **Review relevant information** – A list of important documents and other materials is provided in at the end of this document under

"Resources." Use these resources to educate yourself, your colleagues, and your clients. Many of these and additional resources are available online through the National Concrete Pavement Technology Center (CP Tech Center) Concrete Pavement Sustainability website (www.sustainPCCpave.com).

- **Learn how to design for what you need –** Excessive overdesign is wasteful, and underdesign results in unacceptable performance. Understand the principles and advantages of the mechanistic-empirical approach and the mechanistic approach to pavement design, so you can implement an appropriate approach for a given project. Learn how to collect the required data and use the most advanced tools to ensure that the design meets the project needs.
- **Learn how to approach design holistically –** Understand the principles of incorporating pavement support conditions, material availability and properties, the environment and weather conditions, traffic, community considerations (see principle 2), etc., into sustainable pavement design and construction. In addition to determining slab thickness, other important design elements include materials selection, joint spacing, load transfer, drainage, supporting layers, and surface texture (Smith and Hall 2001; Taylor et al. 2006).
- **Enhance educational programs –** Academic and developmental programs for new and practicing professionals need to be revised to address sustainability issues.
- **Use available tools and develop needed ones**. Learn about and implement current sustainable materials and practices. Encourage and support the development of needed materials and practices.

Principle 2: Design to Serve the Community

The second principle is obvious, yet is often overlooked. It is often referred to as context-sensitive design (CSD), which entails meeting the needs of not only the user but also the adjacent communities and the environment. The key to successfully employing this principle is recognizing that a single approach does not meet all needs.

For example, surface texture created to increase skid resistance and enhance safety has been demonstrated to have a significant impact on noise generation through tire-pavement interaction. The noise issue has been raised by communities adjacent to roadways (Rasmussen et al. 2007). By listening to feedback from local communities, research was conducted to identify factors contributing to the objectionable noise; see figure 3 (Rasmussen et al. 2008). Mitigation strategies have been developed that have resulted in safe and quiet concrete riding surfaces.

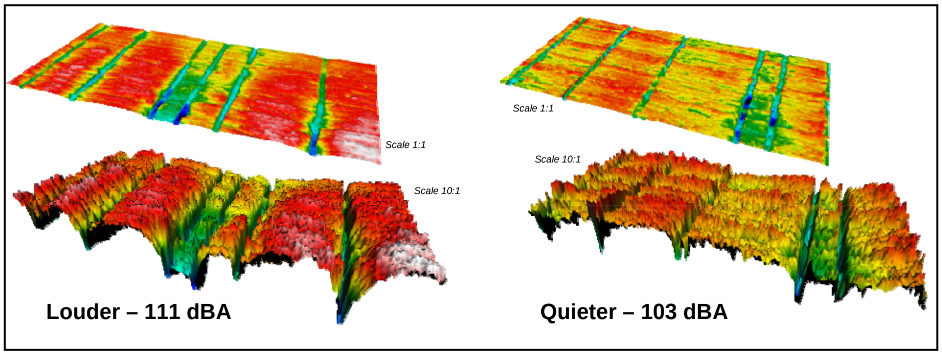


Figure 3. RoboTex scans of 100×200 mm samples showing variability of transverse tined surface and its effect on noise level (adapted from Rasmussen et al. 2008)

“[D]esigning to serve the community will result in . . . projects that reflect a sense of the place where they are built . . .”

But the story does not end there. The same communities that object to noise generated on a high-speed roadway may have a different set of criteria for local, slow-speed roads serving their neighborhoods. In such locations, tire-pavement–generated noise may be far less an issue than aesthetics, high reflectivity, or surface drainage. It is even possible that an urban neighborhood might desire that “roughness” be designed into the surface to produce a calming effect on vehicles exceeding the speed limit and to create a more livable community.

It must be recognized, of course, that the needs of rural communities will differ from those of urban communities, as well as those of the “natural community,” including the health of flora and fauna and the quality of air and water.

Successfully implementing this principle requires early involvement of everyone who is affected through a collaborative, interdisciplinary approach. Public involvement must be early and continuous. Although this will take time, it will ultimately result in increased societal acceptance and project efficiency by reducing expensive and time-consuming reworking of the project at a later date.

In the end, designing to serve the community will result in the construction of concrete pavement projects that reflect a sense of the place where they are built and that meld physically and visually within the surrounding environment and community; see figure 4. More detailed information on CSD can be found at/www.contextsensitivesolutions.org/.

Specific activities that can be immediately adopted to advance this principle for concrete pavements include the following:

- **Involve key stakeholders** – At the earliest stages of design, involve key stakeholders in the process to create a concrete pavement system that will enhance the livability of the community. Stakeholders include

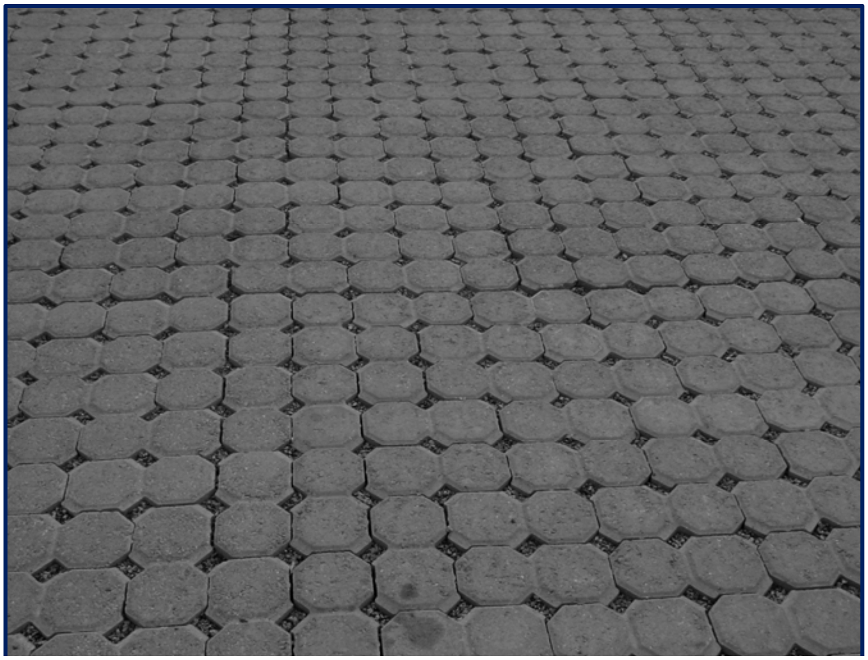


Figure 4. Concrete paver blocks make aesthetically pleasing, well drained pavements for low-volume streets, parking lots, etc.

not only community members, representatives of the transportation agency, and interested organizations, but also the designer, materials suppliers, and contractor.

- **Take advantage of concrete's versatility –** Look for opportunities to take advantage of concrete's versatility for creating highly functional, economical pavements that also meet environmental and social needs. Communities may be interested in concrete's ability to incorporate color and texture into aesthetically pleasing patterns, enhance surface drainage, demarcate pedestrian crossings, and provide a highly reflective surfaces. Consider ways to incorporate concrete's functionality with art, such as the I-35W Bridge reconstruction in Minneapolis, MN (ACI 2009) (some details about this project are provided under principle 7 beginning on page 27).

Principle 3: Choose What You Use

Often, little thought is given to the materials used in a concrete pavement other than whether they meet the specifications. The use of long-established specifications is appealing, but the automatic application of the same specifications year after year creates a barrier to the acceptance of rapidly evolving sustainable practices. A case in point is the use of recycled concrete, either as aggregate in new concrete or even as a base course underlying new pavement. Although concrete is the most recycled material in the United States—about 140 million tons per year (CMRA

2009)—many barriers still exist to using recycled material in concrete pavements.

For example, the single largest concrete recycling project ever undertaken was the complete recycling of Denver Stapleton Airport's pavements, which yielded 6.5 million tons of aggregate, much of which was used in concrete as aggregate (CMRA 2009). Yet the Federal Aviation Administration (FAA) did not have a specification in place for the use of recycled concrete as a base material (Item P-219) until its most recent Advisory Circular (AC 150/5370-10C), which was released in September 2007. And although many agencies, including the FAA, permit the use of coarse aggregate derived from recycled concrete, it is still uncommon in most locales. Specifications, test methods, acceptance criteria, and best practice recommendations are needed to ensure that use of recycled concrete as aggregate is increased without compromising the quality of the final concrete pavement.

One premise of sustainable design is to use local materials to minimize transportation costs and the associated environmental and social impacts. Thus, the first element of this principle is to use the material closest to the project, which of course is the existing pavement structure. Whether it is concrete, hot-mix asphalt (HMA), or a combination of the two, the existing pavement surface and supporting layers can all be effectively used in the construction of new concrete pavement, with a significant positive impact on sustainability.

Innovative in-place recycling techniques have recently been employed on existing concrete as well as HMA pavements, saving money while further reducing the environmental and social impacts of construction; see figure 5.

The Recycled Materials Resource Center (RMRC 2009) provides a good starting point to investigate various recycling options, and a list of additional references is found in the "Resources" section at the end of this document. The shift in thinking that must occur is that the existing roadway is not something to be disposed of, but instead is a source of valuable raw materials (e.g., a technical nutrient) for the reconstruction of the new pavement and an opportunity to eliminate waste (McDonough and Braungart 2002).

To the degree possible without sacrificing pavement quality, additional materials should be sought from local sources. This requires both a knowledge of availability as well as an in-depth understanding of the engineering properties of the material being considered for use. It is not uncommon to find that a local material, such as coarse aggregate, has an

Figure 5. Paving trains recycle existing pavements in place

undesirable property such as poor wear resistance, susceptibility to freeze-thaw damage, or potential alkali-silica reactive (ASR) properties. A key to enhancing the sustainability of the concrete pavement is to not reject these materials out-of-hand, but instead to understand the limitations inherent in the material and thoughtfully address the limitations through proven technologies.

For example, an aggregate with poor wear resistance can still be used, just not at the surface; thus two-lift concrete paving could be effectively used to address this limitation. Similarly, ASR-susceptible aggregates can be used if care is taken in selecting the cementitious material type and content. Replacement of portland cement with certain industrial residuals such as select fly ashes and slag cements or even naturally-derived pozzolans such as volcanic ash, calcined clays, or rice husk ash is extremely effective at mitigating ASR while reducing the environmental footprint of the concrete (more on this below). Thus, being smart in selecting materials can significantly improve the overall sustainability of the project.

And finally, choosing what you use might mean transporting some materials a great distance to overcome potential limitations in the locally available materials. In such cases, it is essential to minimize the amount of material imported to reduce the cost and the environmental and social impacts of transportation. Blending a freeze-thaw–durable, large-sized coarse aggregate with locally available intermediate-sized aggregate that has sufficient durability due its smaller size is one example of this approach.

“Next to water vapor, carbon dioxide contributes more to the earth’s ‘greenhouse effect’ than any other atmospheric gas.”

To recap, the primary strategies used in this principle are as follows:

- **Eliminate the concept of waste** – Look first to the existing pavement as a source of raw materials for the new pavement.
- **Understand the availability and properties of all local materials** – Take advantage of designs that use them effectively. This might mean mitigating limitations.
- **Use materials transported over great distances judiciously** – Blend them with local materials to maximize the overall sustainability of the project.

Principle 4: Less is More

Another common-sense principle of sustainable design is “less is more.” Other factors being equal, a design that uses less virgin material is generally more sustainable. One element of this concept was discussed under principle 1: Avoid wasteful overdesign. The focus of principle 4, however, is on reducing the use of portland cement, the manufacture of which is expensive and energy-intensive and generates harmful emissions.

Next to water vapor, carbon dioxide (CO_2) contributes more to the earth’s “greenhouse effect” than any other atmospheric gas. In 2007, about 1.5 percent of the total anthropogenic (resulting from human activity) CO_2 generated in the United States resulted from the manufacture of portland cement. Portland cement production is responsible for about 90 to 95 percent of all concrete-related CO_2 emissions and 85 to 90 percent of concrete’s embodied energy.

During the portland cement (ASTM C150) manufacturing process, the production of clinker accounts for most emissions and energy use. Approximately 0.96 ton of CO_2 is generated per ton of clinker (0.92 kg CO_2 per kg of plain portland cement). Fifty-five to 60 percent of the total CO_2 generated is produced due to the high-temperature calcination (decomposition) of limestone (calcium carbonate, $CaCO_3$). Calcination drives off CO_2 and creates lime (CaO), a primary component of clinker. The other 40 to 45 percent results from the combustion of fuel to create the necessary kiln temperatures to produce clinker, and from final processing/grinding of the clinker with calcium sulfate (gypsum) to control concrete setting.

Modern cement plants are becoming increasingly efficient, often burning biomass and waste fuels to reduce CO_2 emissions. Still, it is unlikely that the amount of CO_2 produced per ton of clinker can be dramatically reduced. The proportion of clinker to cement, however, can be reduced. Under current ASTM C150 standards, cement manufacturing companies are now allowed to replace up to five percent of clinker with limestone with no specified limit on processing additions (although other limits in the specification effectively control the amount that can be added). This allowance directly reduces clinker content of portland cement.

Another way to reduce CO_2 emissions related to cement manufacturing is simply to reduce the demand for portland cement. Even small reductions of portland cement content in concrete pavements will yield significant environmental savings. Multiple strategies can be employed to do this.

The first strategy is to replace some portland cement in concrete mixtures with supplementary cementitious materials (SCMs). These include certain reactive industrial byproducts such as fly ashes (figure 6), slag cement, and silica fume.

Figure 6. Fly ashes from two sources

Supplementary cementitious materials also include certain naturally derived pozzolans like volcanic ashes and calcined clays (ASTM C618 Class N). Replacing one percent of portland cement with SCM(s) can result in an approximately one percent reduction in CO_2 production and energy consumption per unit of concrete. Using SCMs in concrete mixtures can also yield other benefits, including increased economy and enhanced concrete durability. Therefore, their appropriate use should always be considered.

Cement manufacturers offer various blended hydraulic cements, which are composites of portland cement and SCM(s). Blended hydraulic cements (ASTM C595) include slag or pozzolan. Typical portland cement replacement levels for pavements can be as high as 50 percent for slag blends.

Performance-specified hydraulic cements (ASTM C1157) are manufactured blended cements in which the composition of portland cement and SCMs is not restricted. The kilograms of CO_2 generated per kilograms of blended hydraulic or performance-specified hydraulic cement can be reduced as much as 30 percent or more compared to portland cement.

In addition to manufactured blended cements, another way to incorporate SCMs in concrete mixtures is to add them to the mixture at the concrete plant. The concrete producer can choose to include SCMs such as fly ashes, slag, natural pozzolans, and/or silica fume along with portland cement, or with a manufactured blended cement, as part of the batching process.

A second strategy for reducing the amount of portland cement in concrete is to reduce the total cementitious materials content. Traditionally, mixtures used for concrete pavements have often had a minimum cement content of 564 lbs/yd^3 (six-sack mix). However, the use of optimized aggregate gradations is allowing a significant reduction in cementitious materials content, with some state departments of transportation using mixes with as little as 470 lbs/yd^3 (Taylor et al. 2006).

Such mixes can have the additional benefit of being less prone to segregation and yet easily consolidated during slipform paving operations. Further, the resulting concrete is generally less prone to shrinkage and other negative effects resulting from high cement paste content.

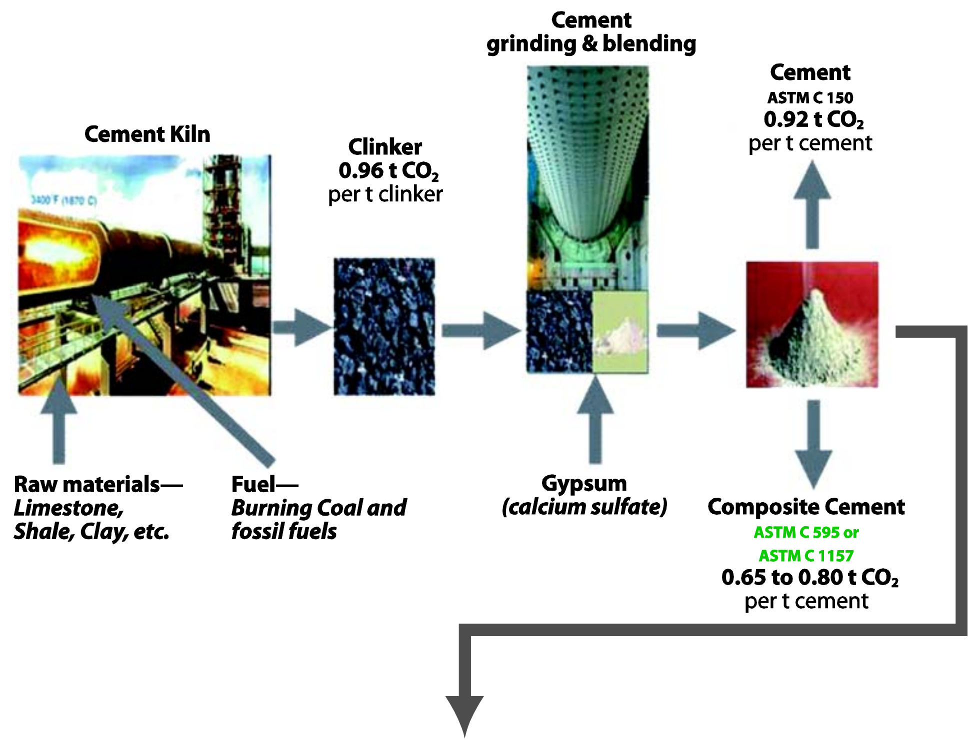
Figure 7 illustrates the reduction in CO_2 production realized by using less portland cement in concrete. The figure shows the amount of CO_2 produced as a result of (left to right) clinker production, portland cement (ASTM C150) production, and blended cement (ASTM C595 or ASTM C1157) production.

The table included within the figure clearly shows how concrete mixture designs that reduce the total cementitious content and/or replace some portland cement with SCMs can play an important role in reducing CO_2 emissions.

In closing, the primary strategies used to meet the principle of “less is more” can be summarized as follows:

- **Avoid wasteful overdesign –** See principle 1.
- **Reduce the amount of portland cement in concrete mixtures –** Include SCMs by using blended hydraulic cements (ASTM C595) and/or performance-based hydraulic cements (ASTM C1157) or by adding SCMs at the concrete plant. Use optimized aggregate gradation to allow a reduction of total cementitious materials content.

These strategies will not only reduce the environmental impact of concrete pavement but, if done correctly, should also result in more economical concrete with enhanced durability.



Impact of Cement and SCMs on CO_2 per Cubic Yard of Concrete

Cementitious lbs/yd³	% SCM	CO_2 lbs/yd³
564	0	527
470	0	442
376	0	356
564	25	404
470	25	351
376	25	271
564	50	282
470	50	234
376	50	190

Figure 7. Amounts of CO_2 produced at various stages of concrete production (based on Roumain 2009; Marceau et al. 2007)

Principle 5: Minimize Negative Impact

This principle encompasses ways to improve several construction and operational impacts that directly contribute to the sustainability of concrete pavement during the construction and operational phases of the life cycle. These impacts include the following:

- Noise – from construction and from traffic
- Safety – Wet weather and night-time driving

- Delays during new construction and during rehabilitation
- Pollution, particulates, and waste generated by construction and traffic
- Water use and treatment of run-off such as sawing slurry
- Energy efficiency – Construction, traffic operations, and urban lighting
- Urban heat island effect, or the observation that higher temperatures exist over built-up urban areas

It is impossible to cover all these impacts in detail in this document, but excellent sources of information are listed in the "Resources" section at the end of this document. In general, construction that enhances sustainability will seek to minimize noise levels; provide a safe environment for workers; minimize disruption of service to the travelling public and community; produce fewer emissions, particulates, and construction waste products; reduce water use; and increase efficiency of equipment and processes; see figure 8.

"... [M]inimize noise levels; provide a safe environment for workers; minimize disruption of service ... ; produce fewer ... waste products; reduce water use; and increase efficiency ...."

Figure 8. Sustainable practices can be as basic as maximizing the efficiency of haul trucks

Once constructed, the concrete pavement should provide a quiet and safe surface under vehicle operations, require minimal preservation and rehabilitation through its life, effectively address water run-off, improve the energy efficiency of vehicles operating on it through reduced rolling resistance, reduce the energy required for artificial lighting, and mitigate the heat island effect through the pavement's reflectivity.

Recently completed research has determined ways that concrete pavements can be constructed or restored to be extremely quiet and safe through the use of drag-textured or longitudinally tined surfaces or through diamond grinding (Rasmussen et al. 2007). There have also been tremendous advances in minimizing water use during construction through the re-use of wash water and through treating run-off from pervious surfaces (NRMCA 2009).

Interest in mitigating the urban heat island effect continues to increase, with the use of reflective paving materials, including conventional concrete, being recommended as a mitigation strategy (EPA 2009). Additives that can further increase the reflectivity (albedo) of concrete, such as slag cement or light-colored fly ash, are also recommended.

The practical strategies that can be employed to address principle 5 can be summarized as follows:

- **Reduce noise during construction and operations** – Noise must be reduced during construction and while the concrete pavement is in use. Recent research has determined that various types of surface textures, including various drags and longitudinal tining, can be constructed in fresh concrete to reduce traffic noise while maintaining safety. Traffic noise can be significantly reduced in existing concrete pavements through diamond grinding.
- **Establish incentives –** Incentives should be established to reduce emissions, particulates, and waste during construction.
- **Adopt strategies to minimize water use –** Strategies to minimize water use in construction, including the re-use of wash water, should be adopted.
- **Add pervious concrete to toolbox –** Pervious pavement should be part of storm water management plans for low-volume applications.
- **Use light pavement surfaces in urban areas –** In urban areas, the use of light-colored, highly reflective pavements can mitigate the heat island effect. Conventional concrete pavement is effective, and even greater reflectivity can be obtained with slag cement or light-colored fly ash. These measures will also help reduce artificial lighting needs.

Principle 6: Take Care of What You Have

“. . . [A] proactive, aggressive approach to pavement maintenance has become more important.”

This principle emphasizes the need to take care of existing pavements. Like any product, with time and use concrete pavements eventually deteriorate. Just as vehicles that are well maintained keep their value longer and can provide more miles of service, pavements that are well maintained deteriorate more slowly and have longer service lives.

Many concrete pavements have been over-designed and/or over-built. This was possible when premium materials were readily available and when adequate roadway budgets allowed a wide margin for design and construction. Today, mix materials have changed, performance requirements have become more demanding, and budgets have shrunk. As a result, mixture designs and construction practices have become more complex, and a proactive, aggressive approach to pavement maintenance has become more important. Ensuring that today’s concrete pavements meet or exceed their 35-year and longer design lives requires holistic quality control during all stages of pavement life, including design, construction, and preservation and rehabilitation.

A proactive approach to sustainable pavements through preservation and rehabilitation requires agencies to

- Focus more time and effort on up-front evaluation of existing pavement conditions.
- Stay informed about new or improved preservation and rehabilitation technologies and practices.
- Systematically deploy optimum preventive maintenance activities, preserving pavements in good condition and extending their high level of service.
- Systematically deploy optimum preservation and rehabilitation technologies and solutions resulting in smoother, more durable pavements with improved surface friction characteristics.

One of the most important, but easy to ignore, elements of such an approach is preventive maintenance. Preventive maintenance activities are accomplished when a pavement is still in good condition. With minimal investment, these activities restore or enhance and extend a pavement's original level of service.

The window for preventive maintenance is approximately 10 to 15 years. Conducting timely, appropriate preventive maintenance on a routine basis can extend a pavement's life significantly. The most common preventive maintenance treatments are partial-depth repairs, full-depth repairs, dowel-bar retrofit, joint resealing and crack sealing, and diamond grinding.

Diamond grinding is typically used to restore ride quality after repairs are completed. This technique also improves skid resistance and significantly reduces tire-pavement noise and can be applied two or three times over the life of the pavement (Correa and Wong 2001). The technique was first used on a section of I-10 in California in 1965, and the same section was subsequently ground in 1983 and again in 1997. This section is still in service today, carrying 2.25 million equivalent single axle loads (ESALs)

Placing a thin unbonded concrete overlay can improve ride quality and pavement surface characteristics after maintenance repairs. Such an overlay can also enhance structural capacity and extend pavement life.

If appropriate and timely maintenance is not carried out, a pavement's condition will continue to deteriorate. Studies have shown that once a pavement's condition has deteriorated to the point that only 40 percent of its life remains, the rate of deterioration accelerates. Then, pavement condition can drop as much as 60 percent in only 12 percent of design life.

Once a pavement's condition is beyond the preventive maintenance window, the pavement has entered the rehabilitation phase and requires structural restoration.

One of the most effective rehabilitation strategies is the use of bonded or unbonded concrete overlays; see figure 9. Unbonded overlays in particular are high-performing rehabilitation strategies for concrete, asphalt, and composite pavements (Harrington 2008). By taking advantage of the existing pavement's remaining structural capacity, an overlay requires only a minimum of new material to restore or even enhance the pavement's structural and functional performance.

"By taking advantage of the existing pavement's remaining structural capacity, an overlay requires only a minimum of new material to restore or even enhance its . . . performance."

Figure 9. Concrete overlays can restore or enhance an existing pavement's functional and structural performance

As with any other structure, there comes a time when a concrete pavement has reached the end of its service life. However, the concrete can still be recycled into the base of a new pavement, in place or elsewhere, or as aggregate for new concrete. In recent years, dramatic improvements have been made in recycling of concrete pavements.

As discussed above, a proactive, life-cycle approach to pavement preservation and rehabilitation is no longer an option. Fortunately, highway agencies have access to information about a variety of effective, concrete-based maintenance and other preservation and rehabilitation strategies to preserve the equity in existing pavements and enhance their functional and structural capacity for less than the cost of reconstruction. Many such strategies, some mentioned briefly above, are described in the *Concrete Pavement Preservation Workshop* (Smith et al. 2008).

To effectively apply principle 6, several strategies should be followed:

- **Factor in anticipated preservation** – Once design life is selected, design and construct concrete pavements to meet the design objectives, factoring in anticipated preservation. If the design life is anticipated to be greater than 30 years, additional thickness to accommodate at least one diamond grinding should be designed for the pavement.
- **Systematically manage asset**s – Apply asset management strategies to use preservation funds effectively. It is well known that maintaining a concrete pavement in good condition is far more cost-effective and thus sustainable than letting the condition slip until major rehabilitation is required.
- **Consider life-cycle costs –** Economics is one of the three pillars of sustainability, and it is critical that the application of concrete life-cycle parameters be understood and applied. Life-cycle cost analysis (LCCA) has been used for a number of years, but most approaches are too simplified and do not necessarily capture the full economic benefits derived from concrete pavements. At minimum, appropriate estimations of initial costs, the timing and costs of preservation and rehabilitation, and the value at the end of life are needed.
- **Extend life with overlays –** If rehabilitation is required, various concrete overlay options exist that can be used to restore functional and structural capacity while maintaining all of the positive features inherent in a concrete surface.

Principle 7: Innovate

Adopting a sustainable approach to pavements requires agencies and industry to develop new ways of thinking and doing. We can no longer base decisions on economic impacts alone, especially first costs. We must consider environmental and social impacts as well, spanning the entire pavement life cycle. Developing win-win-win solutions challenges our abilities to create and innovate.

An important innovation under development is high-SCM content cementitious binder systems. Variations of such systems were used in elements of the I-35W Bridge reconstruction project in Minneapolis; see table 1 (ACI 2009). The piers contained only 15 percent portland cement (with 18 percent fly ash and 67 percent slag cement). This system resulted not only in economic savings but also in enhanced constructability. The heat of hydration was significantly reduced, and thus thermal stresses in the large piers were mitigated during construction. This system also had significant environmental benefits, as it reduced the carbon footprint and embodied energy of the concrete mixture by approximately 75 percent. This bridge was aesthetically enhanced with gateway sculptures (30 ft [9 m]) tall). Concrete for the sculptures contained an innovative new cement that removes carbon monoxide, nitrogen oxides, and sulfur dioxide from the atmosphere by photocatalytic reaction; see figure 10.

Table 1. Concrete mixtures used on the reconstructed I-35W bridge (ACI 2009)

Component	Specified Strength (psi)	w/cm	Cementitious Materials				
			Total (lb/ yd^3)	Portland Cement (%)	Fly Ash (%)	Slag (%)	Silica Fume (%)
Super-structure	6500	0.35	700	71	25	–	4
Piers	4000	0.45	575	15	18	67	–
Footings	5000–5500	0.45	< 600	40	18	42	–
Drilled Shafts	5000	0.38	< 600	40	18	42	–

Figure 10. Gateway concrete sculptures at each end of the I-35W bridge (Photo courtesy of FIGG Bridge Engineers, Inc., and Tim Davis)

Social benefits of the mixtures used in the I-35W Bridge project are more difficult to quantify. They include a reduced amount of waste material (fly ash and slag) going to landfill and a lighter-colored concrete, which reduces the urban heat island effect.

Another emerging technology related to cements is reduced carbon dioxide (CO_2) binders (e.g., magnesium silicates, geopolymers) and binders that sequester CO_2 during their production. Although these binders are currently under development, it is easy to imagine that in the not-too-distant future concrete pavements will be constructed from low- to no-CO_2 cement–based binders.

Aggregates manufactured from CO_2 and seawater may someday be available. Such aggregates could make concrete of the future a CO_2 sink instead of a source (Constantz and Holland 2009).

“The key to enacting this principle is creating partnerships . . .”

Many other innovations are already beginning to impact the concrete paving industry positively, including overlays, two-lift construction, internal curing, and precast pavement elements, to name a few. Life-cycle based approaches encourage innovations such as these.

The key to enacting this principle is creating partnerships among various concrete pavement funding agencies, designers, materials suppliers, contractors, and other interested organizations and community representatives. Essential to such partnerships is shared risk. Adopting innovative approaches is always more challenging than doing what is familiar. If unexpected results occur, it is important to determine what went wrong, correct it for the next iteration, and ultimately adopt those technologies that prove to be promising.

The following activities can help agencies adopt innovative solutions:

- **Develop organizational culture of innovation –** Develop a culture of innovation within your organization, where innovation is encouraged and, to the degree possible, rewarded. Start small and build on success, using a truly grassroots approach to transformation. Small, enthusiastic groups are a great beginning.
- **Engage stakeholders through modern media –** Engage stakeholders in the process while seeking input and addressing concerns. Be cognizant that communication has been revolutionized through the use of the Internet, and use this media to communicate to the broader community.
- **Share risk –** Adopt mechanisms to share risk when innovative solutions are being tried for the first time. Investigate the use of demonstration projects to feature emerging technologies.
- **Learn from mistakes –** Mistakes will be made as innovations are being implemented. This must not be an excuse to abandon an

innovative approach, but should instead be viewed as an opportunity to learn and improve. Only through understanding failures will advances be made.

The approaches suggested for each of the seven principles are provided in a matrix of pavement life-cycle stages; see the appendix.

HOW CAN SUSTAINABILITY BE MEASURED?

Ideally, an eighth principle would be "Measure." The best way to determine a pavement solution's sustainability would be to employ a methodology that measures and compares economic, environmental, and societal factors influenced by the pavement over its entire life cycle; see figure 11.

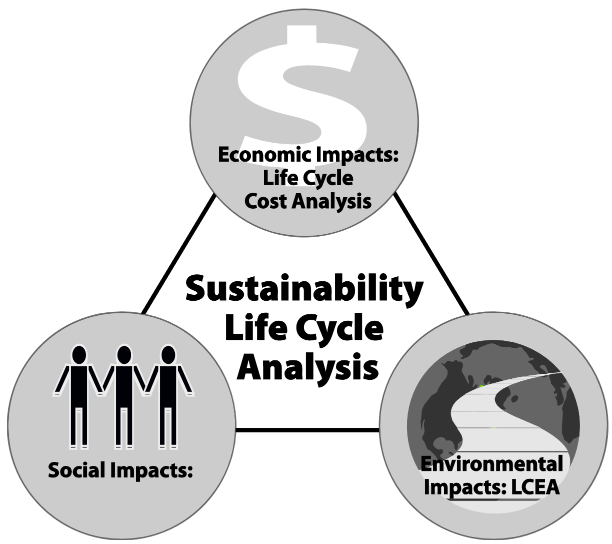


Figure 11. Economic, environmental, and social factors must be identified, measured, and balanced

The methodology could be used in several ways:

- To benchmark current practice and assess improvements as they are implemented
- To compare different systems or solutions on an equitable basis
- To assess the relative benefits of alternative approaches to design, materials selection, etc.

However, such a comprehensive evaluation methodology is not yet readily implementable. Although economic factors have been identified and can be measured, a suite of appropriate environmental and social factors has not yet been identified or generally accepted by the industry, and corresponding measurement tools are not generally available.

The topic of measuring sustainability is extremely complex, and considerable debate regarding the details is ongoing. This section briefly describes some of the economic, environmental, and social factors, or parameters, considered to be the most critical contributors to the triple bottom line of sustainability; see figure 11.

Economic Factors Related to Sustainability

Good engineering practice for any project or system balances the need to minimize economic costs with the need to maximize efficiency, quality, and longevity. However, if attempts to minimize economic costs focus primarily on first (or initial) costs, engineers miss the opportunity to make informed decisions that affect future generations and long-term pavement sustainability. Therefore, economic costs should be analyzed across a system's entire life cycle using a life-cycle cost analysis (LCCA) method, such as the RealCost program (FHWA 2009).

An LCCA is based on sound economic principles. In terms of dollars, the method considers the time-value of money, initial and anticipated future costs, and ultimate value at the end of service life. Most LCCA approaches used by agencies include only agency costs, such as the costs of initial construction, preservation, and rehabilitation, as well as salvage value. It is possible, and maybe even desirable, to include user costs in the LCCA. Such costs include, for example, financial costs to the traveling public caused by road-preservation and maintenance activities. If included, user costs can quickly swamp agency costs. Still, this type of LCCA can provide a framework for considering trade-offs between user costs and agency costs.

Other economic costs that can be considered include the financial cost of environmental cleanup if a significant environmental impact is anticipated. Additionally, if a carbon cap and trade system is adopted, analyzing the economic impacts may provide one means of assessing, through an LCCA, the environmental impacts of the production of carbon dioxide.

Environmental Factors Related to Sustainability

Currently, environmental factors contributing to the sustainability of concrete pavements can be assessed in one of two ways. The first is to use one of the emerging rating systems based loosely on the Leadership in Energy and Environmental Design (LEED) green building rating system

(USBGC 2008). For concrete pavements, a few examples of such systems include the following:

- Green Roads: a rating system for pavements under development at University of Washington (Greenroads 2009)
- GreenLITES: a certification program instituted by the State of New York (NYSDOT 2008)

Whereas LEED has evolved over the last decade into a widely accepted approach for rating the environmental impact of buildings, systems for rating the environmental impact of pavements are still in the early stages of development and have yet to be broadly vetted. Further, by their very nature, rating systems simplify complex issues and may deliver an inappropriate assessment of some innovative pavement solutions. Thus, care must be exercised when using such systems, as inappropriate measures and weightings may be applied to establish the rating. In time, as these systems evolve and improve, they likely will provide a simple approach to quickly assess the environmental factors related to concrete pavement sustainability.

In contrast to the rating systems and their inherent simplifications, the second method for assessing environmental factors—a detailed life-cycle environmental assessment (LCEA)—offers a more complex approach. The primary example is the International Organization of Standardization's (ISO) guideline ISO 14040:2006, *Environmental Management – Life-Cycle Assessment – Principles and Framework* (ISO 2009). This guideline describes how to conduct an LCEA that accounts for all the individual environmental flows to and from a concrete pavement throughout its entire life cycle, from material extraction and processing through construction, operations, restoration, and rehabilitation, and ultimately to the end of service life and disposal/recycling.

Although the ISO guideline describes the LCEA principles and framework, it does not describe the LCEA technique in detail or specify methodologies for individual phases of the LCEA. Instead, several companies have developed methodologies that adhere to ISO 14040:2006 guidelines. These include the Athena Institute (2009), BASF (2009), and the RightEnvironment (2009), among others.

Similarly, work conducted for the Portland Cement Association to develop a life-cycle inventory (LCI) for portland cement concrete followed ISO 14040 guidelines (Marceau et al. 2007).

Based on these efforts and others, the following environmentally based parameters can be recommended for assessing the environmental impact of pavements in general and concrete pavements specifically:

- Embodied energy

- Emissions/global warming potential
- Toxicity potential
- Raw materials consumption
- Waste generated

Embodied Energy

Embodied energy is the amount of energy required to collect a raw material or produce a manufactured product and transport it to a destination for use. Before this parameter can be used correctly in an LCEA for pavements, the embodied energy for a broad range of raw materials and manufactured products used in pavement systems needs to be determined and a database of this information made available.

Because transportation is included in this value, less embodied energy will be incurred if local materials can be used (e.g., all things equal, recycling concrete on-site will have less embodied energy than concrete transported and processed off-site). In addition, the embodied energy attributed to recycled or reclaimed materials, such as recycled concrete aggregate, fly ash, or slag cement, is zero (excluding transportation).

Emissions/Global Warming Potential

Emissions to the atmosphere include those that contribute to global warming, such as carbon dioxide, methane, nitrous oxide, chloro-fluorocarbons (CFCs), water vapor, and aerosols. A useful practice is to convert all such materials to a carbon dioxide (CO_2) equivalent related to global warming potential (GWP). For example, methane has a weighting of 25 because its contribution to global warming is 25 times more potent than that of CO_2 (ISO 2009).

It is also possible to quantify the mass of dust and particulates released from the pavement system (VanGeem 2007). While many of these data are available, a database of GWP for American products and materials is required.

Toxicity Potential

Toxicity potential can be assessed by compiling data about the known toxicity of compounds emitted from the pavement system and their effects on humans, animals, and plants (ISO 14040). A database is needed that catalogs the toxicity of materials that may be used in pavement construction, such as crystalline silica or materials that emit volatile organic compounds.

Raw Materials Consumption

Pavements consume significant volumes of extracted raw materials. Aggregates, for example, comprise 100 percent of untreated support layers and about 70 percent of pavement slabs. Many state road agencies are experiencing difficulty in obtaining acceptable aggregates because of the depletion of current sources and social pressures not to expand or open new quarries.

It is thus increasingly attractive to recycle concrete and other reclaimed materials as aggregate. Changes in pavement design, material selection, or construction that reduce the use of non-renewable materials enhance a pavement's sustainability.

Waste Generated

Waste generated from all stages of a pavement's life cycle can become economically, environmentally, and socially burdensome. Sustainability literature considers waste in terms of its potential to be used in other processes or products. Some waste streams can be composted into "natural nutrients" or re-manufactured into "technical nutrients" (McDonough and Braungart 2002; Senge et al. 2008).

From this point of view, the volume and nature of waste from pavement systems can be a measure of their sustainability. Figure 12 illustrates these concepts for concrete pavements.

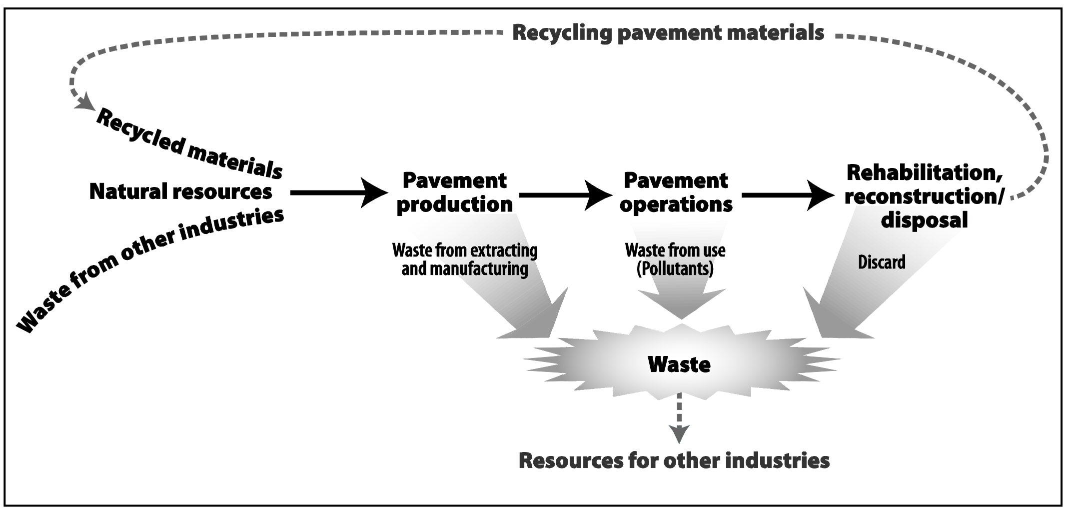


Figure 12. Reducing waste in pavement production by increasingly treating recycled pavement as a "technical nutrient" or a "natural nutrient" (adapted from Senge et al. 2008)

Societal Factors Related to Sustainability

Societies, particularly the United States, are utterly dependant on the ability of people and goods to move rapidly and efficiently from place to place. The mobility that pavements provide is one critical social factor in their overall sustainability. Another social factor is pavements' effect (by virtue of their appearance, location, contribution to traffic noise, impacts on safety, etc.) on the quality of life in surrounding communities.

Although the pavement industry has made progress in developing tools for analyzing two sustainability factors—LCCAs for analyzing economic factors and rating systems and early LCEAs for measuring environmental factors— no system is yet available for assessing social factors. The following are several potential parameters that would need to be included in such an assessment.

Safety

The first concern of any transportation agency is to provide roadways that are safe to the user and the community. This means that, among many other factors, the surface must provide skid resistance while minimizing splash and spray, be neither pot-holed nor faulted, and enhance night-time and poor-weather visibility for the safety of drivers and pedestrians. If included in the LCCA, the cost of accidents, injuries, and loss of life will quickly overwhelm an economic analysis.

User Delays

Another important factor is that pavement systems must facilitate the rapid and efficient movement of vehicles. Time wasted due to congestion during maintenance and reconstruction activities increases the stress of drivers and negatively impacts their health. Delays also reduce productivity and can have large negative economic impacts. The surrounding community and other populations are also affected by delays, as idling vehicles consume fuel and generate pollutants. If included in calculations, the value of people's time wasted in traffic will normally dominate an LCCA. Therefore, great benefit is derived from pavement systems that maximize the free flow of traffic over their life cycle through being rapidly constructed, requiring a minimum of preservation and rehabilitation during their service life, and requiring replacement only at long intervals.

Noise

Noise—that generated during pavement construction or maintenance as well as tire-pavement noise from traffic—is another social factor. Noise considerations quickly become complex. For example, in urban environments, considerable funding can be expended in building sound barriers to insulate surrounding communities from expressways. The social benefits of such barriers depend on their effectiveness in sound reduction, their overall neighborhood aesthetic, and their potential effect on property values. It may be preferable to mitigate noise generation at the source by, for example, constructing quieter pavement surface textures.

Energy

Critical to users of pavements is the energy consumed in travelling over the surface. Because of the high volume of roadway traffic for many pavements, even a minor reduction in fuel consumption for a given pavement type provides a significant positive impact on sustainability. In addition, agencies responsible for artificial lighting to illuminate roadways at night can realize significant energy savings when the pavement surface is highly reflective. This reflectivity not only has economic value, but also environmental and social value due to reduced emissions from energy

WHERE DO WE GO FROM HERE?

As discussed above, concrete pavement stakeholders already have a toolbox of practical solutions that can have a positive impact on pavement sustainability. In addition, progress is being made on developing life-cycle systems that will analyze economic, environmental, and social factors related to pavement sustainability. Development of such decision-making tools is part of a strategic national plan for research in concrete pavement sustainability: the Sustainability Track of the Long-Term Plan for Concrete Pavement Research and Technology (CP Road Map).

The Sustainability Track focuses on developing projects and securing related sponsor support to improve materials and practices in concrete pavement design, construction, operations, preservation, rehabilitation, and recycling (things we do now) in ways that that reduce life-cycle costs, improve the environmental footprint, and increase the benefits to society (things we need to learn to do better).

An initial, extensive literature search for the track has revealed little published information on sustainability and sustainability science related to concrete pavements and particularly reflecting North American practice. Some notable exceptions are efforts conducted by the Cement Association of Canada (CAC), the American Concrete Pavement Association (ACPA), and the Portland Cement Association (PCA).

However, a thorough review of the literature did reveal many gaps in research, technology, and implementation that need to be filled through additional research. These gaps are categorized in a "framing document" (www.cproadmap.org/publications/ track13CSframing.pdf) to guide track leaders in prioritizing research:

- Materials
- Design
- Construction practices
- Preservation, rehabilitation, and recycling
- Economic life-cycle cost analysis
- Environmental life-cycle analysis
- Other environmental and social considerations

Most of these categories are the focus of other tracks in the CP Road Map. The Sustainability Track coordinates and helps prioritize sustainability-related work in these categories among all the tracks. To implement what already is known, several early products are recommended under the Sustainability Track, including the following:

- Ongoing refinement of this briefing document to reflect an evolving understanding of sustainability and describe the current state of the practice.
- Development of a best practices training manual and implementation package for concrete pavement sustainability. This manual will provide detailed technical information to engineers, material suppliers, and contractors and will have immediate and measureable impacts on improving the sustainability of concrete pavements.
- Organize and conduct a conference on the sustainability of concrete pavements that systematically addresses economic, environmental, and societal impacts; emerging technologies; and legislative/policy initiatives to increase awareness of how the various factors interact.
- Work with federal and state agencies to create demonstration projects that feature sustainable solutions and effectively communicate the successes of these projects.

The vision of the CP Road Map's Sustainability Track is to identify, quantify, and enhance the characteristics of concrete pavement systems that help enhance roadway sustainability in terms of economic, environmental, and societal considerations throughout the pavement's life cycle (design, materials selection, construction, operation, preservation, rehabilitation, and recycling).

Research conducted under the track will contribute to the following goals:

- Development of advanced materials and processes that optimize reuse and conservation and that measurably reduce waste, energy consumption, water usage, and pollutants generated during all phases of the pavement's life cycle.
- Creation of innovative designs that make full use of the versatility of concrete as a paving material to improve pavement sustainability.
- Adoption of construction practices that directly enhance the overall sustainability of concrete pavements through increased efficiency, reduced emissions and waste, and decreased social disruption.
- Application of preservation, rehabilitation, and recycling strategies that are applicable to newly constructed concrete pavements and that enhance the sustainability of the existing network of concrete pavements.
- Refinement of life-cycle cost analyses to fully account for the economic attributes of sustainable concrete pavements.
- Acquisition, preservation, and distribution of data as part of an environmental life-cycle inventory (LCI) that accounts for all the

individual environmental flows to and from a concrete pavement throughout its entire life cycle and the adoption of an internationally recognized environmental life-cycle analysis (LCEA) approach that examines the environmental aspects of concrete pavements through their life cycles.

- Identification and quantification of social considerations that are affected by concrete pavement and inclusion of these considerations in the integrated design process.
- Adoption of European practices and models regarding identifying and quantifying environmental considerations (e.g., theRightEnvironment).
- Development of strategy selection criteria to assist in the decision making process and to allow various alternatives to be compared based on economic, environmental, and social considerations.
- Distribution of technology transfer for existing concrete pavement technologies that support the "triple bottom line" of economic, environmental, and societal sustainability.
- Coordination and collaboration, with work being performed under other CP Road Map research tracks.

CONCLUSIONS: CHALLENGE AND OPPORTUNITY

"The Concrete pavement community is uniquely . . . situated to take up the challenge and make a significant contribution to sustainable development."

Sustainable development is the essential challenge of the 21st century. The concrete pavement community is uniquely and strategically situated to take up the challenge and make a significant contribution to sustainable development. As outlined in this document, concrete pavement stakeholders have significant opportunities, now and in the future:

1. Begin by adopting a focus on and commitment to sustainability that incorporates, to the extent possible, economic, environmental, and social factors in concrete pavement design and engineering.
2. Follow the seven principles outlined in this document and implement existing concrete pavement materials and practices that contribute to pavement sustainability through all the stages of a pavement's life cycle—including design, materials selection, construction, operation, preservation, rehabilitation, and recycling.
3. Support and participate in efforts to systematically quantify pavement sustainability.
4. Support and participate in efforts to develop new concrete-based paving innovations that will further enhance pavement sustainability, including efforts outlined in the Sustainability Track of the CP Road Map.

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RESOURCES

Centers

CP Tech Center: www.cptechcenter.org
Materials in Sustainable Transportation Infrastructure: www.misti.mtu.edu/index.php

Associations and Societies

American Concrete Institute Committee 130 Sustainability: www.concrete.org/COMMITTEES/committeehome.asp?committee_code=0000130-00
American Concrete Pavement Association: www.acpa.org/
American Society of Civil Engineers: www.asce.org/professional/sustainability/
Cement Association of Canada: www.cement.ca/
Context Sensitive Solutions: www.contextsensitivesolutions.org/
Green Highways Partnership: www.greenhighways.org/
International Grooving and Grinding Association: www.igga.net/
Portland Cement Association: www.cement.org/SD/index.asp
Recycled Materials Resource Center: www.recycledmaterials.org/
National Ready Mix Concrete Association: www.nrmca.org/sustainability/index.asp

Producers

BASF: www.basf.com/group/corporate/en/content/sustainability/eco-efficiency-analysis/index

LCEA Tools

Leadership in Energy and Environmental Design: www.usgbc.org/Default.aspx

Federal

Environmental Protection Agency: www.epa.gov/
Greenroads: pavementinteractive.org/index.php?title=Green_roads
FHWA: www.fhwa.dot.gov/pavement/concrete/
FHWA Context Sensitive Design: www.fhwa.dot.gov/context/index.cfm
Green Streets Calculator: http://1734298.sites.myregisteredsite.com/green11/calculator.aspx
Measure of Sustainability: www.canadianarchitect.com/asf/perspectives_sustainibility/measures_of_sustainablity/measures_of_sustainablity_intro.htm
National Renewable Energy Laboratory: www.nrel.gov/lci/
RealCost: www.fhwa.dot.gov/infrastructure/asstmgmt/rc21toc.cfm