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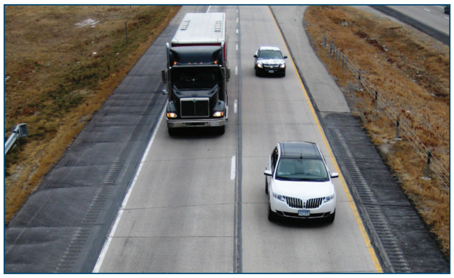
SUSTAINABLE CONCRETE PAVEMENTS:

A Manual of Practice

January 2012



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16. Abstract

Developed as a more detailed follow-up to a 2009 briefing document, *Building Sustainable Pavement with Concrete*, this guide provides a clear, concise, and cohesive discussion of pavement sustainability concepts and of recommended practices for maximizing the sustainability of concrete pavements.

The intended audience includes decision makers and practitioners in both owner-agencies and supply, manufacturing, consulting, and contractor businesses. Readers will find individual chapters with the most recent technical information and best practices related to concrete pavement design, materials, construction, use/operations, renewal, and recycling. In addition, they will find chapters addressing issues specific to pavement sustainability in the urban environment and to the evaluation of pavement sustainability.

Development of this guide satisfies a critical need identified in the Sustainability Track (Track 12) 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 by the concrete pavement stakeholder community, including Federal Highway Administration, academic institutions, state departments of transportation, and concrete pavement–related industries. It outlines 12 tracks of priority research needs related to concrete pavements. CP Road Map publications and other operations support services are provided by the National Concrete Pavement Technology Center at Iowa State University. For details about the CP Road Map, see www.cproadmap.org/index.cfm.

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Sustainable Concrete Pavements: A Manual of Practice

January 2012

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MISSION

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

PHOTO CREDITS

Unless otherwise indicated in the text, all photographs and illustrations used in this guide were provided by the technical editor and co-author Dr. Peter Taylor.

DISCLAIMERS

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The content of this guide reflects the expertise and contributions of the technical advisory committee, whose members represent the wide variety of discrete processes and variables, including regional issues, that must be considered to effectively optimize the sustainability of concrete pavements. While the authors generated the overall content, it was the technical advisory committee's careful reviews of drafts, thoughtful discussions, and suggestions for revisions and refinements that make this guide a straightforward, comprehensive resource for practitioners. We appreciate the invaluable assistance of the committee members:

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PREFACE

Sustainable Concrete Pavements: A Manual of Practice is a product of the National Concrete Pavement Technology Center at Iowa State University's Institute for Transportation, with funding from the Federal Highway Administration (DTFH61-06-H-00011, Work Plan 23). Developed as a more detailed follow-up to a 2009 briefing document, *Building Sustainable Pavement with Concrete*, this guide provides a clear, concise, and cohesive discussion of pavement sustainability concepts and of recommended practices for maximizing the sustainability of concrete pavements.

The intended audience includes decision makers and practitioners in both owner-agencies and supply, manufacturing, consulting, and contractor businesses. Readers will find individual chapters with the most recent technical information and best practices related to concrete pavement design, materials, construction, use/operations, renewal, and recycling. In addition, they will find chapters addressing issues specific to pavement sustainability in the urban environment and to the evaluation of pavement sustainability.

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Chapter 1

INTRODUCTION

Tom Van Dam

Peter Taylor

It is becoming increasingly apparent that a host of human activities and development practices are negatively affecting the economic, environmental, and social well-being of the planet, putting future generations of humanity, as well as of other species, at risk. Confronted with this reality, stakeholders in the pavement industry are being challenged to adopt practices that maintain economic vitality while balancing environmental and societal needs.

At the same time, stakeholders are facing other challenges: Pavements are aging and deteriorating; one-third of the road system, about 1.3 million miles, is in poor condition or worse, receiving a grade of D- in the American Society of Civil Engineers report card (ASCE 2009A). Traffic volumes and vehicle loads continue to increase, putting more demands on the already stressed pavement system and, in major metropolitan areas, resulting in serious congestion problems. Roadway agency budgets continue to fall short of needed funds, with an estimated $115.7 billion annual shortfall from funding required to substantially improve pavement conditions. These challenges exist not only in a time of economic uncertainty but also within the developing realization that the environmental and social impacts of these pavements systems are great.

The people responsible for the management, design, construction, maintenance, and rehabilitation of the deteriorating network of pavements are overwhelmed, recognizing that the current approach to solving problems inherent in the nation's pavement infrastructure is not sustainable. What is needed is a new approach, the implementation of truly sustainable pavement solutions that result in reduced economic cost over the life cycle, lessened environmental impact, and enhanced societal benefit, while maintaining the system in a high level of service for perpetuity. Recognizing this, many public agencies are adopting more "sustainable" practices and are beginning to rate, incentivize, and even award projects based on their demonstrated ability to enhance sustainability.

Yet, the basic questions remain: What is sustainability? What attributes of concrete pavements can make them a sustainable choice? Why is an emphasis on sustainability important for the concrete pavement industry?

1. What is Sustainability?

A basic definition of sustainability is 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, 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).

Typically, three general categories (or pillars) of sustainability are recognized: economic, environmental, and social. When activities are sustainable, no pillar is ignored; instead, a workable balance among the three often-competing interests must be found. Together, the three pillars form what is commonly called the "triple bottom line" (Elkington 1994). This concept can be expressed graphically as shown in Figure 1.1, which illustrates that sustainable solutions are those that incorporate all elements of the triple bottom line.

Although this is a common definition of sustainability, it is somewhat dissatisfying as it doesn't define what is and is not important and it doesn't provide clear direction as to what must be done differently in the future to improve upon the present. This manual provides such definitions and directions, as they are currently understood, regarding concrete pavements.

Figure 1.1 Graphical representation of sustainability's "triple-bottom line" of economic, environmental, and societal considerations

Balancing economic, environmental, and societal factors for a pavement project requires identifying applicable factors in each category, collecting data for the factors to be evaluated, applying tools to quantify the impact of each factor, and assessing the combined impact of the factors in relationship to one another. Complicating the process is the fact 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. In other words, assessment of the sustainability of a project will require the use of a robust, sophisticated analysis.

It is recognized that a complete assessment of sustainability is beyond the current state of the practice and, in truth, may be impossible. Still, the application of available tools will assist in making incremental progress in achieving more sustainable concrete pavements.

2. Concrete Pavements and Sustainability

Concrete pavements suffer from a perception that they contribute a considerable amount of carbon dioxide (CO_2) to the atmosphere due to the use of portland cement that binds the aggregates together. Although portland cement manufacturing is an energy intensive process and does result in significant CO_2 emissions, partly due to the pyroprocessing required and partly due to the calcination of limestone (discussed in Chapter 4), advances in cement production have greatly decreased these impacts relative to even a few years ago. In addition, and just as important, modern concrete for pavements uses less portland cement per cubic yard relative to past practices, and thus concrete pavements have a lower carbon footprint than at any time in history. Further, future innovations will ensure additional improvements in reducing the carbon footprint and energy use over the next decade. When all aspects of sustainability are considered, especially when accounting for the pavement's life cycle, properly designed and constructed concrete pavements are clearly part of a sustainable transportation system.

Following are a few general attributes of concrete pavements that can make them a sustainable choice:

- Long life: Achieving the desired design life with minimal future preservation activities results in reduced user delays and associated economic and environmental impacts over the life cycle.
- Smooth, quiet, and safe over the life cycle: Motorists experience a comfortable ride; drag is minimized for enhanced vehicle efficiency; pavement surface visibility and skid resistance are maximized through minimal preservation activities.
- Increased use of industrial residuals and reduced use of non-renewable resources.
- Fully recyclable.
- Cost effective: Demonstrated over the life cycle, concrete pavements preserve their equity long into the future.
- Minimal impact to the surrounding environment: In-place concrete pavements have no adverse effect on, and are not adversely affected by, atmospheric conditions, the natural environment, etc.
- Minimal traffic disruption during construction and preservation activities.
- Community friendly: Aesthetically pleasing, appropriately textured, light colored surfaces reduce ambient noise, emissions, surface run-off, urban heat, and artificial lighting needs, resulting in a positive local and global impact.

Strategies for design, material selection, construction, operation, maintenance/rehabilitation, and reconstruction/recycling are already being implemented that create concrete pavements with these attributes. Some of these strategies have been part of standard practice for over 100 years, resulting in incredible longevity and cost effectiveness, the hallmarks of concrete pavement. Others strategies, although demonstrated, are in the initial phase of implementation. This manual of practice focuses on concrete pavement strategies that can be readily implemented to enhance sustainability.

3. Why Should the Concrete Pavement Industry Care about Sustainability?

Before considering strategies to increase sustainability, it is first necessary to take a step back to consider why this is important to the concrete pavement industry.

First, sustainability is not really new; it simply raises the bar for good engineering. Good engineering has always entailed working with limited resources to achieve an objective. What has changed is the scope of the problem, along with the period of time over which a project is evaluated. Whereas in the past economic factors were paramount, now environmental and social factors must be considered equally with economic factors. Whereas in the past initial costs and other initial impacts were often paramount, now the span of time in the analysis is increased to the entire life cycle of a project, and all impacts (both positive and negative) are considered from the point of inception (e.g., mining of raw materials) to end of life (e.g., recycling). This type of analysis is often referred to as a “cradle to cradle” analysis (McDonough and Braungart 2002).

Such an all-encompassing scope over such a long analysis period requires a systems approach to fully realize the opportunities to implement sustainable design. At this juncture, sustainable design is not about achieving perfection but about balancing competing and often contradictory interests to bring about incremental change. Although most civil engineers find the idea of sustainability as the new standard for good engineering to be a challenging prospect, many find it engaging as well. As sustainable design continues to evolve, so will the role played by the concrete pavement industry.

Second, sustainability is increasingly being demanded by a diverse number of stakeholders. One major group of stakeholders is the public. ASCE’s Board of Direction recently approved the following statement (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).

This statement recognizes that one of the driving forces for the changing role of the civil engineer as a "sustainer" is the "public's growing awareness" that a more sustainable built environment is achievable. Civil engineers are being required to examine alternative solutions that a few years ago might not have been considered. This idea is clearly annunciated in the integrated global aspirational vision statement adopted at *The Summit on the Future of Civil Engineering* held in 2006, 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 large aspiration, reflecting the responsibility entrusted by the public to those charged with designing, constructing, operating, preserving, rehabilitating, and recycling infrastructure including concrete pavements.

Another group of stakeholders, more directly relevant to the concrete pavement industry, includes local, state, and federal pavement owner agencies. As mentioned previously, various agencies have begun to require that sustainability metrics be measured on paving projects and may use such metrics in the selection process for future transportation projects.

Third, today's increasing focus on sustainable infrastructure offers an opportunity for the concrete pavement industry to communicate the positive contributions inherent in concrete pavement. Because of its versatility, economy, local availability, and longevity, concrete is the most commonly used building material on the planet; it is not hyperbole to say that modern civilization is literally built on concrete. Due to the sheer volume of concrete in use and its many sustainable attributes, it has a relatively large environmental footprint as well as immense positive impacts on sustainability. The concepts related to sustainability provide a positive language through which industry can communicate the good being done through the use of concrete pavement rather than solely disputing unjustifiable perceptions of harm.

Fourth, adopting sustainability principles and practices will make the concrete pavement industry more attractive to a younger workforce. Peter Senge et al. (2009), in their book, *The Necessary Revolution: How Individuals and Organizations are Working Together to Create a Sustainable World*, state that employees are making career choices based on an organization's commitment to sustainability. Yet even ASCE, in the last sentence of the Board of Direction's statement cited earlier (ASCE 2009B), has recognized that civil engineers are often perceived as part of the problem, not the solution: "Civil engineers are not perceived to be significant contributors to a sustainable world." With this backdrop it is clear that, to attract the young talent needed for the future, industry must change such negative perceptions through the advancement of sustainable concrete infrastructure, including pavements.

And, finally, enhancing sustainability will make the concrete pavement industry more innovative and more competitive. This can be observed already through such diverse innovations as in-place recycling of existing concrete pavement, two-lift construction, safe and quiet surface characteristics, pervious concrete, optimized aggregate gradations that reduce cementitious material content, and the trend toward concrete with higher supplementary cementitious material (SCM), to name a few. Each of these examples clearly demonstrates positive economic, environmental, and social impacts. Emerging concrete technologies 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 challenge to the industry is to step out of the box and, instead of focusing 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.

4. Organization of This Manual

Fortunately, many best practices already exist for constructing new concrete pavements as well as preserving or rehabilitating existing ones in a manner that significantly contributes to the sustainability of the nation's highway system. Decision makers, engineers, material suppliers, and contractors need practical guidance on adopting these solutions and considering their relative benefits in the context of limited budgets, increased performance requirements, and congested traffic situations. This manual of practice is designed to help, as summarized in the following brief description of its chapters:

1. *Introduction* – This chapter generally defines sustainability and its significance for the concrete pavement industry.

2. *Pavement Sustainability Concepts* – This chapter focuses on specific attributes of pavements, with a particular emphasis on concrete pavements, that impact sustainability. The life cycle, including cradle-to-gate and ideal cradle-to-cradle closed loop systems, is described. Technologies that extend pavement life and/or reduce the use of energy intensive and environmentally damaging materials and practices will be emphasized. This chapter presents a conceptual cradle to grave approach to concrete pavement, introducing the specific topics discussed in detail in Chapters 3 through 10.

3. *Designing Sustainable Concrete Pavements* – Sustainability is not an accident, instead requiring a thoughtful, systematic approach to concrete pavement design. Sustainable solutions make the best use of locally available materials without compromising, and possibly even enhancing, pavement performance. Design attributes that have been shown to enhance sustainability, including extended service life designs and two-lift construction, are featured, but emerging concrete pavement systems including precast concrete pavements and thin concrete pavements are also introduced.

4. *Sustainable Concrete Pavement Materials* – Materials used to make concrete for pavements have a large impact on the sustainability of the pavement. This chapter details the importance of making durable concrete that withstands the environment during its service life. It also emphasizes the need to use the appropriate amount of cementing materials, discussing the advantages of reducing portland cement through good mixture design and the use of supplementary cementitious materials, including fly ash and slag cement. The emergence of lower energy, lower emissions cements (including portland-limestone cements, carbon neutral/sequestering cements, and geopolymers) is also discussed. The chapter concludes with a discussion of concrete making materials, with specific emphasis on the use of recycled and industrial byproduct materials used as aggregate.

5. *Construction* – Various elements of construction have an impact on the overall sustainability of a concrete pavement. Obvious elements include the energy consumed and waste generated during the constructions process, including emissions and solid waste. Water use during the entire construction process is another important element, as is the generation of noise and particulate matter, especially as it relates to the social impact in urban environments. This chapter discusses these construction-related elements and presents strategies to minimize the environmental aspects of concrete paving project.

6. *The Impact of the Use Phase* – The versatility of concrete as a paving material offers many sustainable attributes that are not always obvious. Operational considerations are an extremely important consideration, as it is estimated that at least 85 percent of the environmental footprint of a pavement is incurred after it is built during its service life. The most prominent impact is from the vehicles operating on the pavement, most notably from the fuel consumed, which is influenced by pavement roughness and possibly by the stiffness of the surface layer. Recent research has focused on the influence of radiative forcing, which is related to surface reflectivity and may be contributing to global climate change even from rural pavements (impacts in the urban environment are addressed separately in Chapter 9).

7. *Concrete Pavement Renewal* – Preservation and rehabilitation play an important role in ensuring concrete pavement longevity while maintaining the highest level of serviceability. As such, they directly contribute to the sustainability of the concrete pavement. This chapter discusses various preservation and rehabilitation strategies that can be applied to increase concrete pavement sustainability, directing the reader to appropriate sources for further information. The main focus of this chapter is on how timely and appropriate preservation and rehabilitation can be used to enhance sustainability

over the life cycle. The uses of diamond grinding and concrete overlays are featured.

8. *End of Life Recycling Concepts and Strategies* – This chapter discusses the recycling of existing road materials into new pavement. The focus is on recycling concrete, but recycling hot-mix asphalt and unbound granular materials into a new concrete pavement is also discussed. Specific guidance on the appropriate use of recycled material as aggregate in new concrete is provided, as is guidance for its use in supporting layers. Emerging in situ recycling techniques are discussed as a sustainable alternative.

9. *Concrete Pavements in the Urban Environment* – This chapter discusses the unique characteristics of concrete pavement that make it ideal for use in an urban environment. Of specific interest is its high surface reflectivity index (SRI), which can help mitigate the urban heat island effect and decrease the cost of artificial lighting. The urban environment is also a location where photocatalytic cements and coatings can be used to provide additional reflectivity while treating nitrogen oxide (NO_x), (SO_x), and volatile organic compounds. Concrete can also be colored and molded to create aesthetically pleasing designs that not only are beautiful but also can be used to calm traffic in urban neighborhoods, making them more pedestrian friendly. Alternatively, textured concrete surfaces can be designed to be exceptionally quiet for high-speed operations. Addressing surface run-off is another critical need in urban settings, making the use of pervious concrete an ideal choice for many paved surfaces.

10. *Assessment of Pavement Sustainability* – It is essential that the sustainability of pavements be systematically and accurately assessed to recognize improvement and guide innovation. This chapter reviews current approaches to assessing pavement sustainability, including the Greenroads^{TM} rating system. It also describes the rigorous environmental life cycle assessment (LCA) approach as a path to more fully quantify and optimize the environmental factors contributing to the sustainability of concrete pavements.

11. *Conclusions and Future Developments* – This chapter briefly summarizes the information presented in this manual. It also discusses emerging technologies that are not yet ready for implementation but have the potential to significantly impact concrete pavement sustainability within the next decade. Its goal is to inform the reader of developing trends as well as foster innovation and encourage the adoption of technologies that will lead to more sustainable concrete pavements.

Due to the dynamic nature of the topic, this manual is a "living document" that will be revised regularly to reflect evolving understandings of issues related to enhancing concrete pavement sustainability.

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Chapter 2

PAVEMENT SUSTAINABILITY CONCEPTS

Tom Van Dam

This chapter focuses on the broad application of sustainability concepts as applied to the natural world, to pavement systems in general, and then specifically to concrete pavements. It begins with a brief introduction to a systems approach to understanding sustainability, introducing the concept of the life cycle, including cradle-to-grave and cradle-to-cradle closed loop systems. The chapter then discusses the life cycle of concrete pavement and how the adoption of sustainable practices results in continued economic, environmental, and social health. The chapter concludes with a discussion of innovation, describing how innovation is driven through the adoption of sustainability principles.

1. A Systems Approach – Seeing the Big Picture

This manual of practice is specifically written to address the needs of transportation and pavement professionals to facilitate the adoption of sustainable concrete pavement practices. As such, the focus is very specific and the scope is necessarily narrow. Yet it is essential that concrete pavement professionals develop an appreciation of the role they play in creating a more sustainable world by understanding the relationships that exist between the industrial system on which the economy is built and the natural world, which includes social and ecological health.

Until fairly recently, decision making was largely based on consideration of the “bottom line,” which was understood in purely economic terms. In *The Necessary Revolution*, Senge et al. (2008) state that it is not surprising that few people paid attention to degrading social and environmental conditions under this model of industrial activity as it “focuses on parts and neglects the whole.” As a result, achieving immediate tangible economic goals was rewarded while ignoring long-term, larger system needs was largely without consequence. This is evident upon examination of production during the industrial age, in which narrow thinking led to widespread dependency on non-regenerative energy and material resources, inefficient and waste-generating production, and economic growth driven through the consumption of products and services.

Figure 2.1 (Senge et al. 2008) illustrates this model of production, showing how the current industrial system (e.g., goods in production and use) is part of a larger system that can broadly be considered as the natural world. This natural world includes regenerative resources (e.g., forest, croplands, and fisheries) and non-regenerative resources (e.g., oil, minerals). Regenerative resources are part of the ecological system, and as long as such a resource is replenished more quickly than it is consumed, the resource is sustained indefinitely. On the other hand, non-regenerative resources are extracted from the earth, and since they are not regenerated within a useful timeframe, they may in time become depleted. Significantly, the extraction and harvesting of resources and the production and use of goods generate waste. Depending on the nature of this waste, it can compromise the ecological system and its ability to produce regenerative resources that are essential to the health of humanity as well as all life on the planet. Not shown in Figure 2.1, but essential to understanding sustainability, is how the current industrial system impacts social systems (e.g., communities, families, culture).While improving the quality of life in some aspects, the system also results in anxiety, inequality, and stresses on societies that in the extreme are manifest as widespread poverty and war.

As an alternative, Senge et al. (2008) offer the concept of a regenerative circular economy illustrated in Figure 2.2. This economy reflects a movement towards greater use of harvested regenerative resources and a dramatic reduction in accumulating waste, resulting in a more sustainable world in which resources are regenerated and waste minimized or eliminated. In this model, there is still a need for extractive industries, but the greater dependency on renewable resources ensures less system-wide impact due to extraction. It also establishes a close link between economic growth and natural resource regeneration, which requires healthy ecological systems. Biodegradable waste from

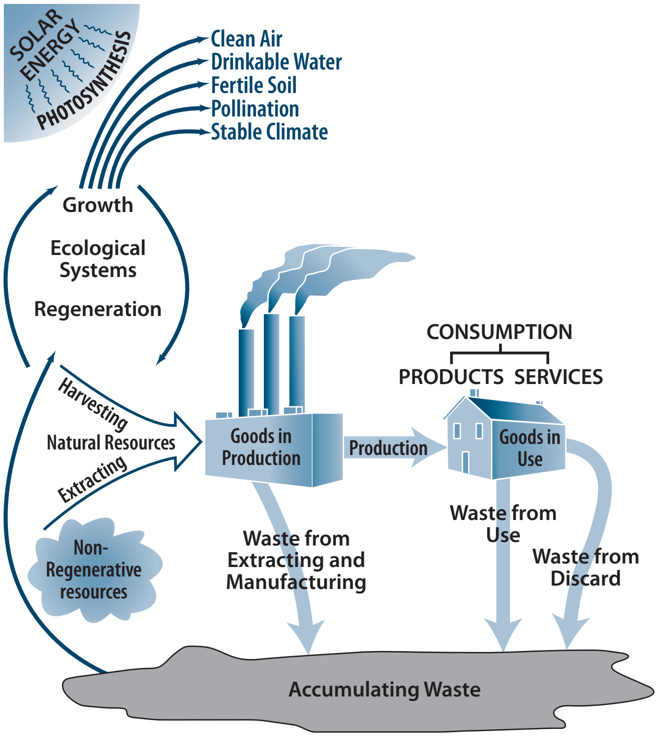

Figure 2.1 Illustration of the current industrial system (Senge et al. 2008)

industrial processes are fed into the ecological system to support resource development. Wastes not used to support natural systems are used as raw materials for other industrial processes, thus resulting in waste minimization while at the same time reducing demands to extract or harvest additional resources. Ideally, the economic system will ultimately mimic that which happens in nature, in which the concept of waste is eliminated and all waste becomes food for another process (McDonough and Braungart 2002).

Inherent in this concept is the understanding that sustainability requires a life-cycle perspective, in which the economic, environmental, and social benefits and costs of any product or service are considered over its entire life. This is partially illustrated in Figure 2.2, which shows material extraction, manufacturing, and goods in use, with a circular flow of natural and technical materials back into regeneration and production.

What is lacking in this illustration is the temporal nature of the life cycle, which in the case of a pavement may be 40 or more years. Conventionally, we think of pavement life as linear, moving from the "cradle" (design, material extraction and processing, and construction) through its service life and finally to the "grave" (pavement removal and reconstruction). This cradle-to-grave concept is counter to sustainability. Sustainability instead requires a "cradle-to-cradle" approach in which the end of life is part of a new beginning (McDonough and Braungart 2002). For concrete pavements, this is simply illustrated in Figure 2.3, in which design, materials processing, construction, operations, preservation and rehabilitation, and reconstruction and recycling are joined in a continuous loop.

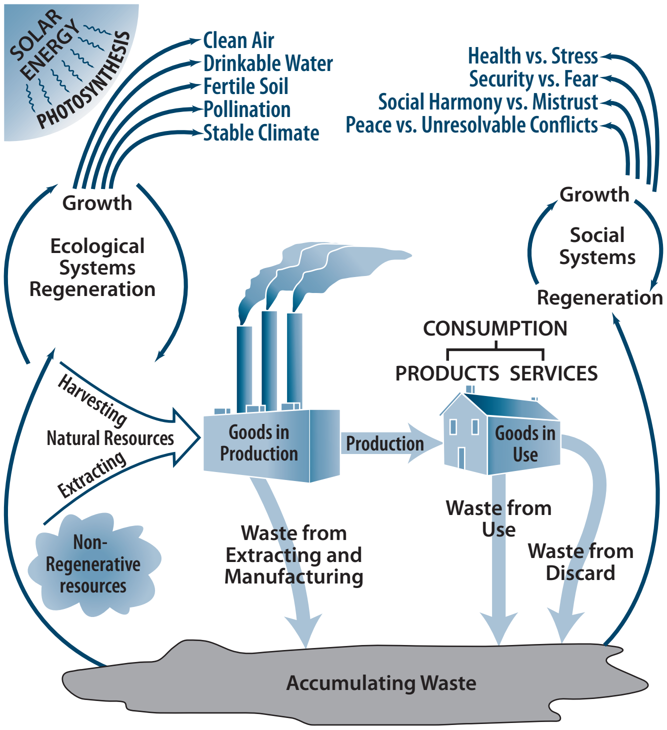

Figure 2.2 Illustration of the regenerative circular economy (Senge et al. 2008)

Although conceptually this may seem overwhelming, 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. In addition, as is discussed in Chapter 10, a number of approaches to assess sustainability are emerging and will soon be available for implementation by the concrete pavement industry, including the use of life-cycle analyses that address environmental impacts over the life of a pavement. Yet, only by stepping away from the larger issues of the economy as a whole and instead focusing on the project level can these overarching sustainability concepts be implemented into actionable and measurable activities that will be used by the concrete pavement industry.

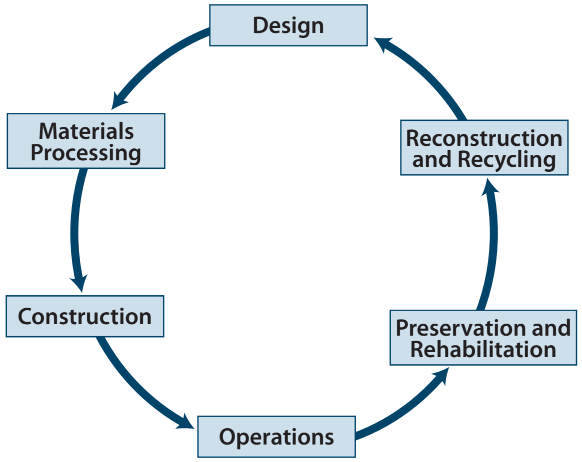

Figure 2.3 The concrete pavement life cycle (Van Dam and Taylor 2009).

To do so, it is first necessary to recognize that a concrete pavement can be considered as a project-level system within the larger system previously discussed. This project-level system has its own context, which is sensitive to the needs defined by the various stakeholders and the environmental setting in which the project is to be constructed. The context establishes the constraints under which project decisions are made, from which the following two additional sustainability components are identified (Muench et al. 2011):

- *Extent* – Extent represents the spatial and temporal constraints and limits of the project-level system, including such items as project length, right-of-way, service life, height restrictions, construction working hours, and so on. These constraints establish the boundaries within which sustainability of the project can be assessed.
- *Expectations* – Expectations are the key human value constraints, which include both the economic and social context, used to judge the overall performance of the system. They may include performance of individual design elements, the quality of some aspect of the overall project, or how an outcome beyond the project-level system is addressed.

Already, there has been modest movement within the concrete paving industry to adopt practices that support sustainability at the project level that have broader system-wide sustainability impacts. For example, a common technical nutrient used in concrete production is slag cement, which is a byproduct of another industry and improves the long-term properties of concrete (meeting project-level constraints) while reducing system-wide environmental impacts (e.g., lowering the energy use and emissions of the constructed pavement). Other recycled and industrial byproduct materials (RIBMs) that are used in concrete include fly ash, recycled concrete aggregate (RCA), and air-cooled blast furnace slag, to name a few, all of which are addressed in later chapters in this manual of practice.

However, sustainability is much broader than the application of a number of individual activities (such as RIBM use). Focusing narrowly on individual activities will result in minor improvements but will miss out on the much greater opportunity to significantly enhance the sustainability of the project-level system, as well as positively impacting the system as a whole. Without a guided and committed approach to implementation, the adoption of sustainable practices by the concrete pavement industry will languish. To move sustainability from a philosophical concept to implementable practices will require the adoption of the following two additional components of sustainability (Muench et al. 2011):

- *Experience* – Experience represents both what has been learned and the ongoing learning process, including technical expertise, innovation, and knowledge of applicable historical information.
- *Exposure* – Exposure represents ongoing educational and awareness programs for all stakeholders, including the general public, agencies, engineering professionals, and contractors.

The purpose of this manual of practice is to help meet the objectives of these two sustainability components, conveying industry experience and exposing stakeholders in the concrete pavement industry to the concepts and implementation of sustainable practices. The next section of this chapter will introduce some of the specific sustainable features of concrete pavements, linking these features to the various phases illustrated in Figure 2.3. Subsequent chapters expand on each phase, providing actionable items that can be implemented today and that will directly enhance the project-level sustainability of concrete pavements.

2. Concrete Pavements

Many features of concrete pavements should be assessed when considering them from a sustainability perspective. Further, innovative features continue to emerge that result in additional enhancement to the sustainability of concrete pavements. Figure 2.4 illustrates a few of these features, each of which is described in detail in subsequent chapters of this manual of practice. The purpose of this section is to describe the relationship between these features and the life-cycle phases illustrated in Figure 2.3, as well as among the features themselves. The complex nature of these relationships demonstrates the need for the application of a holistic systematic approach when considering the sustainability of concrete pavement.

Design Phase

It is fitting that the design phase is the first to be discussed, as it is only through thoughtful and deliberate design that sustainability can be achieved. Design of concrete pavements has traditionally focused on slab thickness design, although other design details, including joint spacing and load transfer, slab support considerations, drainage, and edge support to name a few, have long been recognized as being of equal or greater importance (Smith and Hall 2001).

These design details are directly considered in the new AASHTO DARWin-ME™ Mechanistic-Empirical Design Guide (MEPDG), which provides a rigorous approach to considering the effect of multiple design variables to assist in optimizing the design for given conditions. Use of the MEPDG approach is growing and will likely become the norm over time. Authorities are developing local calibration data for the system or using a locally modified version.

In addition to these traditional design considerations, elements illustrated in Figure 2.4, including surface texture, light color, long life, and improved storm water quality can also be considered during the design process. It is easy to see how these elements, although selected at the design phase, interact directly with other phases of the life cycle. For example, quiet surface texturing, light pavement coloration, and improved storm water quality (e.g., pervious concrete) directly impact the use phase, particularly in an urban environment where quiet and cool pavement surfaces have positive social impacts and increased storm water infiltration has broad economic, environmental, and social benefits. Long-life pavements directly impact preservation, rehabilitation, and reconstruction, delaying the timing of future activities and reducing future agency and user costs, thus directly affecting life-cycle economic impacts while reducing future traffic delays and associated environmental and social impacts. It is also clear that design objectives cannot be achieved if not integrated with the materials processing and construction phases, thus necessitating collaboration between the various specialties represented in typical transportation agencies.

The design phase is also where innovative pavement design types, such as two-lift concrete pavement, roller-compacted concrete (RCC), precast concrete and concrete pavers, and thin concrete pavement (TCP) will be considered. The design phase is discussed in detail in Chapter 3 of the manual of practice.

Materials

Material processing is a broad topic that includes material acquisition, material processing, and concrete mixture design and proportioning. Current material acquisition is largely based on extractive industries, such as mining aggregate or raw materials for cement

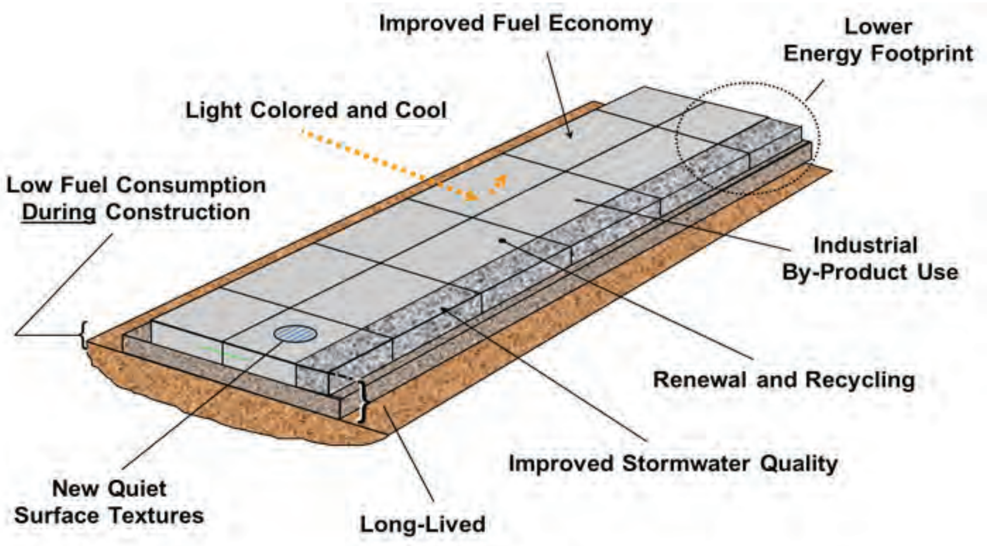

Figure 2.4 Features of concrete pavements that can enhance sustainability (from Wathne 2008)

production. But some material acquisition is from renewable resources (mainly for chemical admixtures), and others are byproducts from other industries (e.g., RCA or supplementary cementitious materials such as fly ash and slag cement). Material processing entails taking the raw materials and making finished materials including cement, crushed and blended aggregates, admixtures, and so on. Material processing can often be more energy intensive than construction activities, meaning that small benefits in processing will lead to substantial savings in the whole life cycle. Mixture design and proportioning is the creation of material blends that meet the engineering requirements and are subsequently placed during the construction phase.

Materials have a major impact on all other life cycle phases, as they often provide project-level constraints during the design phase and strongly influence the construction, preservation/rehabilitation, and reconstruction/recycling phases, and even impact the operational phase. Regarding sustainable features illustrated in Figure 2-4, material processing factors most directly influence decisions impacting the use of industrial byproducts, reduced energy footprint, light color, and long-life.

This phase is discussed in detail in Chapter 4 with additional discussion on recycled concrete in Chapter 8.

Construction

The construction phase includes typical concrete plant batching and mixing operations, transportation of materials from stockpiles and the concrete plant, paving operations, and post-paving activities. This phase can have a large impact on the sustainability of the concrete pavement over the life cycle because, even if the best design and materials are used, poor construction makes it unlikely that the concrete pavement will achieve its design objectives or expected service life. With respect to Figure 2.4, the construction phase directly impacts long life, the creation of a quiet surface texture, and low fuel consumption during construction.

Concrete pavement construction is discussed in Chapter 5, which briefly describes specific activities that support enhanced sustainability, including low energy plant operations, recycling water and returned concrete, low-emission equipment, in-place recycling, and local material utilization.

Operations

The operational or use phase of a concrete pavement is rarely considered at the project level unless capacity and congestion are being considered as part of a transportation planning study. Yet, up to 85 percent of greenhouse gas emissions associated with the expected service life of a pavement can be incurred during this phase (Ochsendorf 2010). This is most significant on high-volume roads, where emissions generated by vehicles are a dominant factor. To some degree, it has been found that the rolling resistance of vehicles moving on a rigid surface is less than that of those moving on a flexible surface, but research is still underway to determine the significance of this difference and its impact on fuel efficiency and emissions. What is known to be significant is that fuel efficiency is improved on smooth roads, emphasizing the importance of constructing smooth pavements and then using preservation strategies that reduce roughness (e.g., diamond grinding). These topics are discussed in Chapter 6.

Sustainability attributes of the use phase that are enhanced by the use of light-colored concrete surfaces include improved night-time safety, reduced need for artificial lighting, and reduced urban heat island effect. Improved storm-water quality and quiet surfaces are also benefits realized in the use phase in urban environments. The urban environment also provides an opportunity to use photocatalytic materials integrated into the cement or applied as a coating to treat certain harmful emissions. Such urban opportunities are discussed in Chapter 9.

Preservation and Rehabilitation

Concrete pavement preservation is a strategy for keeping good pavements in good condition. It is not only economically cost effective but also has significant environmental and social benefits. For one, preservation strategies use limited amounts of new materials, reducing the environmental burden of material extraction and processing. Further, preservation techniques entail minimal traffic disruption, reducing emissions and social impacts. And the use of diamond grinding as a preservation strategy not only restores texture to enhance safety, the resulting pavement surface is quiet and smooth, reducing the impact of noise while increasing fuel efficiency.

Preservation is no longer appropriate when the structural capacity of the pavement needs to be improved. At this point, a number of rehabilitation alternatives can be effectively utilized, including the use of concrete overlays. The appropriate and timely use of overlays will take advantage of the remaining pavement structural capacity, extending the pavement service life in a cost-effective and environmentally beneficial manner.

Concrete pavement renewal, which incorporates both preservation and rehabilitation, is discussed in Chapter 7.

Reconstruction and Recycling

The final stage of a concrete pavement's life cycle is reconstruction and recycling. In-situ recycling of concrete pavement, generally as a new subbase or base layer is a viable alternative, with the economic and environmental advantages of minimal material transportation. The use of screened RCA as a new base or concrete is also a possibility. One benefit of crushing concrete and exposing it to the atmosphere is that it will sequester atmospheric carbon dioxide through carbonation, an added benefit of recycling. Discussion of these topics, along with the incorporation of other recycled paving materials, including recycled asphalt pavement (RAP), in new concrete pavement is provided in Chapter 8, which focuses on completely recycling the existing structure back into a newly reconstructed pavement.

3. Importance of Innovation

One of the greatest advantages of adopting sustainable concrete pavement practices is in the discovery of things that are yet unknown. Considering economic, environmental, and social factors over the entire pavement life cycle will require a different way of thinking about the concrete pavement industry. Current thinking is driven by the need to meet only the short-term economic bottom line. As this approach gives way to longer-term thinking that considers all three facets of sustainability, innovative solutions will emerge. Implementing new, sustainable solutions can allow the industry to move dynamically forward, realizing multiple opportunities and expanding markets. In contrast, if the industry (represented by all stakeholders, whether owner or client) balks and is unable to move beyond entrenched ideas and technologies, it will be limited in its ability to recognize the opportunities that exist.

Already, a number of technologies are being adopted in response to implementing sustainability principles. As discussed in Chapter 4, the most obvious are changes in cementitious materials and mixture proportioning that have significantly reduced the amount of portland cement contained within a cubic yard of concrete. This has led to a significant reduction in the carbon footprint of paving concrete, with no anticipated decrease in expected performance (many expect better performance) and no increase in cost. Other innovations, including the use of in-situ concrete recycling, recycling water at the concrete plant, pervious concrete, and next-generation quiet texturing, are already becoming mainstream in some markets. Emerging technologies including the use of photocatalytic cements and the inclusion of RAP in concrete mixtures are undergoing field trials in demonstration projects. And, as described in Chapter 10, tools to rate the sustainability of concrete pavements are also emerging and will soon become integrated into common practice.

Further advances are just over the horizon, whether low-carbon to carbon-sequestering cements, innovative designs or materials that result in a significant reduction in pavement thickness, new bio-derived admixtures that enhance the durability of concrete, equipment that rapidly and efficiently recycles concrete in-situ, next generation inexpensive and highly efficient photocatalytic materials, or even pavements that generate electricity to power adjacent neighborhoods. Although the exact nature of these innovations is speculative at this point, as is discussed in Chapter 11, it is a certainty that innovations are underway that will change the nature of the concrete pavement industry and that the adoption of these innovations will be driven by sustainability principles.

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Chapter 3

DESIGNING SUSTAINABLE CONCRETE PAVEMENTS

Tom Van Dam

Sustainability is not an accident. Pavement design plays a strong role in ensuring that the constructed concrete pavement begins its life as a cradle-to-cradle sustainable project. This chapter considers how concrete pavement design plays a strong role in enhancing the sustainability of concrete pavements. The chapter begins by introducing the concept of context sensitive design, which requires the designer to recognize that a single approach to design does not meet all needs, that input must be sought from the various stakeholders, including those representing the natural world, and that the design must be tailored to meet the unique needs of every project. The state of the practice in pavement design is then briefly introduced, including designing for what is needed and avoiding waste inherent in both under-design and over-design. Specific concrete pavement design attributes that enhance sustainability are then presented. Many of these involve improving the interaction between the pavement surface and the environment, whether using specific textures that are quieter, lighter colors that are cooler, patterns that are aesthetically pleasing and safer, photocatalytics that have the ability to treat air pollution, or pervious surfaces that have the ability to improve storm water quality. The chapter concludes with brief introductions to four innovative pavement designs (two-lift, precast panels and pavers, roller-compacted concrete, and thin concrete pavements) that offer opportunities for the designer to further enhance the sustainability of concrete pavements.

1. Context-Sensitive Design

Sustainability requires a thoughtful approach to concrete pavement design. The designer must account for human needs and values defined by the management team and various stakeholders while considering the environmental setting in which the pavement will be constructed (Muench et al. 2011). This approach 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 to design does not meet all needs.

For example, the past practice of transversely tining concrete pavements to create surface texture that increased skid resistance and enhanced safety has been demonstrated to have a significant impact on noise generation through tire-pavement interaction (Rasmussen et al. 2007). The noise issue was raised by communities adjacent to roadways, and, in some cases, concrete pavements were overlaid solely to reduce the noise generated. Because of feedback from local communities, research was conducted to identify factors contributing to the objectionable noise and mitigation strategies have been developed that have resulted in safe and quiet concrete riding surfaces; see Figure 3.1(Rasmussen et al. 2008).

It is recognized that 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, creating a safer and more livable community for the residents. More information on urban environments is given in Chapter 9.

Along the same lines, the needs in a rural environment will differ from those of urban communities. Often, the health of the "natural community," which includes flora and fauna and the quality of air and water, will become increasingly important in rural settings. This is why the designer must be sensitive to the context in which the pavement is being designed.

Successfully implementing CSD requires early involvement of everyone who is affected, including those representing community interests and ecological systems, through a collaborative, interdisciplinary approach. Public involvement must be early and continuous. Although this takes time and effort, it will result in increased societal acceptance and reduced ecological impact, improving 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. More detailed information on CSD can be found at

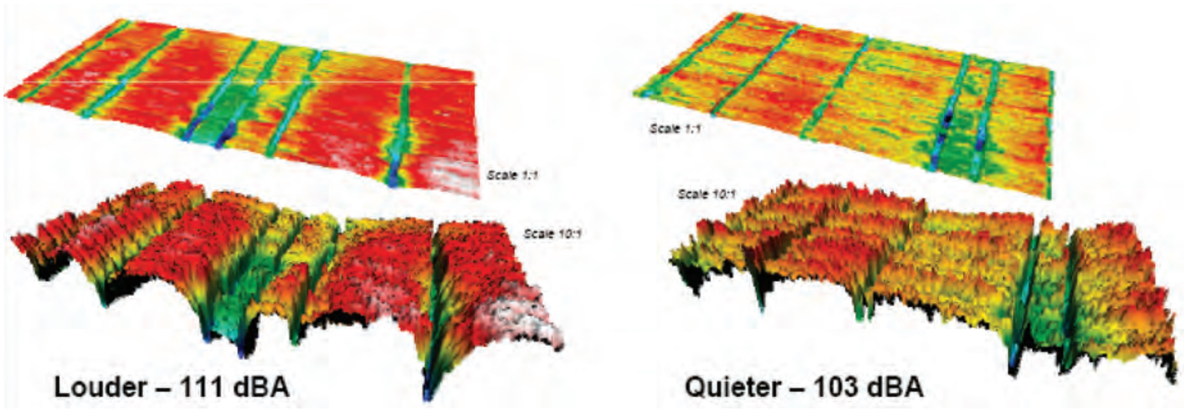

Figure 3.1 RoboTex scans of 100×200 mm samples showing variability of transverse tined surface and its effect on noise level (adapted from Rasmussen et al. 2008)

www.contextsensitivesolutions.org. Specific activities that can be immediately adopted to advance CSD for concrete pavement design 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 agency personnel and interested organizations and community members, plus the designer, materials suppliers, and contractor (if possible). The Missouri Department of Transportation's (MoDOT) recently constructed US 141 "green" project in St. Louis, Missouri, illustrates the power of stakeholder participation, involving the contractor and community representatives in a CSD process in designing a new route that passed through a popular wooded area. By working with the contractor and community, the designer was able to incorporate multiple sustainable elements into the design, allowing MoDOT to develop a showcase project with strong community backing (Jonas 2011).

- *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 highly reflective surfaces.

2. Concrete Pavement Design: The State of the Practice

The state of the practice in concrete pavement design produces long-life pavements that withstand heavy traffic and severe environmental loadings for decades with little need for maintenance or rehabilitation (Tayabji and Lim 2007, Hall et al. 2007). This ability to confidently design pavements that will perform as desired for 40 or more years is one of the most sustainable inherent features of concrete pavements. Because longevity is so important, it must be recognized that long concrete pavement life is about a lot more than just slab thickness. Common design features of long-life concrete pavements include the following (Tayabji and Lim 2007):

- *Adequate structural slab thickness* – Some designs include additional thickness as a sacrificial layer that will be removed during future diamond grinding.

- *Strong, erosion-resistant bases* – Many states use either asphalt- or cement-stabilized bases.

- *Doweled transverse joints or continuously reinforced concrete pavement* – When jointed plain concrete pavement design is used, the joint spacing is relatively short, the joints are doweled, and often highly corrosion-resistant dowels are used.

As discussed by Van Dam and Taylor (2009), a fundamental principle in sustainable design is to design for what you need. This means that the designer should thoroughly understand the principles of pavement design, accurately collect the required data, and use the most advanced design tools available to ensure that project needs are met within the given economic, environmental, and social constraints. Overdesign—in which the concrete slab is designed significantly thicker than required—is wasteful, unjustifiably increasing the economic and environmental burden of the project. But under-design can be even more wasteful, as it will often result in unacceptable performance, premature failure, and the need to apply maintenance and rehabilitation at an earlier than anticipated age at great economic, environmental, and social cost.

The AASHTO DARWin-ME$^{\text{TM}}$ mechanistic-empirical pavement design (MEPDG) approach more thoroughly considers the contribution of material properties, support conditions, climate, and traffic, as well as slab geometry, edge support, and joint load transfer than do empirically-based methods, thus resulting in more accurate designs. Further, a mechanistic approach, which is based on scientific principles, also accommodates innovation much more readily than an empirical approach, which relies on observation, experience, or experiment, thus allowing the designer an avenue to evaluate nontraditional approaches to design and materials selection and proportioning.

As briefly discussed in Chapter 2, pavement design must be approached holistically, with all design elements considered together. In addition to the slab thickness, other important design elements that must be considered include material properties, joint spacing, load transfer, drainage, supporting layers, and surface texture (Smith and Hall 2001, Taylor et al. 2006).

3. Design Attributes Directly Enhancing Sustainability

Depending on context, design attributes specifically focused on enhancing sustainability should be considered. These include such surface features as being aesthetically pleasing, safe and quiet, reflective, and photocatalytic.

As these design attributes are primarily applicable in an urban environment (which is discussed in detail in Chapter 9), they will only be briefly addressed here. But the essential recognition from a design perspective is how each of these features directly influences the way the pavement interacts with the surrounding community and/or ecological system, whether through a reduction in noise, a safer riding surface, improved aesthetics in the community, reduction in air pollution, reduction of the heat island effect, and/or reduction of run-off while improving storm water quality. In fact, many of these features address multiple needs. For example, photocatalytic materials not only help breakdown nitrous and sulfur oxides (NOx and SOx), they also are light colored, addressing the urban heat island effect and perhaps improving storm water quality as well (see Chapter 11).

The new generation of quiet surface textures are also skid resistant, improving safety. Pervious concrete not only improves storm water quality, it also is known to reduce the heat island effect and, if used as a riding surface, is known to be quiet. The use of concrete pavements in heavy traffic locations such as bus lanes and loading docks can be an effective means of reducing pavement distress and the resulting effects of closures for repairs. Thus, an informed designer can package various pavement surface attributes to address multiple sustainability goals. Further, these attributes can be used in combination with some of the emerging innovative design technologies discussed next to great advantage.

4. Alternative and Emerging Design Technologies

Traditionally, concrete pavement design has focused on determining the thickness of a concrete slab, placed as a single lift with one pass of a paver. Recently, a number of alternative paving technologies have emerged that are challenging this traditional way of constructing concrete pavements, offering some unique design opportunities including the following:

- *Two-lift concrete pavement design* – Two-lift pavements are constructed in two lifts, wet on wet, using two slipform pavers one immediately following the other. The concrete mixture in the bottom lift is often different from the mixture in the top lift.
- *Precast concrete pavement systems* – Fabricated off site in precast plants, this type of pavement can offer a number of sustainability enhancements.
- *Interlocking concrete pavers* – Also fabricated off site in a precast plant, pavers provide an aesthetically pleasing surface that can also be pervious, highly reflective, or even incorporating photocatalytics for use in streets and local roads.
- *Roller-compacted concrete (RCC) pavements* – RCC pavement designs use stiff concrete mixtures placed and densified using equipment typical of hot-mix asphalt (HMA) construction. Traditionally used in hydraulic structures, pavement in industrial facilities, and cargo handling areas, it is starting to be used in streets and local roads.
- *Thin concrete pavement (TCP) design* – Based on a patented Chilean design, TCP is characterized by relatively thin slabs with short joint spacing.
- *Pervious pavements* – Pervious pavements allow rainwater to percolate and replenish groundwater rather than requiring rainwater to be handled by a storm water or effluent system.

The following sections briefly discuss each of these innovations and how they can be used in the design of sustainable concrete pavements.

Two-Lift Concrete Pavement

Two-lift concrete paving is not new. In fact, the oldest concrete pavements in the United States, constructed by the R.S. Blome Granitoid Co., were placed as two-lifts, wet-on-wet, with the top lift being a different concrete than the bottom lift. Two-lift construction was also used to facilitate the placement of reinforcing mesh in jointed reinforced concrete; the mesh was set upon the surface of the bottom lift and encapsulated by the top lift. Recently, after examining the excellent performance of two-lift concrete pavements in Europe, there has been a resurgence of interest in adopting modern two-lift concrete pavement design in the United States, as shown by recent demonstration projects constructed in Kansas and Missouri (see www.cptechcenter.org/projects/two-lift-paving/index.cfm).

This pavement system typically consist of a thick bottom lift (typically 80 percent or more of the total thickness) and a thin (20 percent or less of the total thickness) top lift that is optimized for carrying traffic. Many European countries utilize an exposed aggregate surface texture in conjunction with the two-lift construction process.

The potential sustainability advantages of two-lift pavement include the following:

- *Bottom lift* – The concrete mix proportions for the bottom lift can be optimized knowing it will be protected from the elements during construction (as it will be capped with the top lift) and will not be subjected directly to traffic. This means that it can use a higher supplementary cementitious material (SCM) content, higher percentage of recycled aggregate including recycled asphalt pavement (RAP), and aggregates with less stringent requirements (e.g., wear resistance) than normal because the bottom lift will not be exposed to traffic. A broader range of locally available aggregates and higher amounts of recycled and industrial byproduct materials (RIBMs) can be used, and so reduce the environmental footprint of the concrete.
- *Top lift* – The relatively thin top lift is optimized to carry traffic. It often uses wear-resistant aggregate that may have to be transported longer distances and a higher portland cement content, but can do so without significantly impacting the environmental footprint of the pavement due to the thinness of the layer. This ensures good long-term durability and a safe riding surface, especially if the thickness of the top lift is designed for multiple diamond grindings over its life. In the case of the Kansas demonstration project, the use of an exposed aggregate surface was investigated to reduce noise generated from tire-pavement interaction (Shields and Taylor 2009). The Missouri project is experimenting with the use of photocatalytic cement in the top-lift (www.cptechcenter.org/t2/documents/EnvironmentalIssues-Stone.pdf) to treat air pollution. Photocatalytic materials are expensive, and thus using them only in the top lift makes sense to reduce costs without impacting performance.

Experience with two-lift paving in the United States is limited but increasing. Eleven two-lift projects were constructed from 1970 to 1994 (Florida, Iowa, Kansas, Michigan, and North Dakota) (Harrington et *al.* 2010) all are still in service. In 2008, the Kansas DOT constructed over five miles of two-lift pavement on I-70 west of Abilene (Figure 3.2).

The versatility inherent in the two-lift design provides the designer with multiple options to cost effectively integrate one or more sustainable attributes into the new pavement, resulting in economic savings while improving environmental and social performance. It is expected that this versatility will result in the widespread adoption of this technology in the future.

Figure 3.2 Two-lift pavement being constructed in Kansas

Precast Concrete Pavement Systems

Precast concrete pavement systems have a long history, but with recent innovations they will continue to grow in popularity. Precast concrete pavement systems typically consist of individual panels that are one to two lanes in width and 10 to 15 ft in length, depending on the system. The pavement panels are produced in a precast plant, where the material is proportioned, molded, consolidated, and cured under controlled conditions, then shipped to the site where they are assembled on grade.

Fabrication under controlled conditions eliminates a major construction variable—unfavorable ambient weather conditions—which can play havoc on conventionally cast-in-place concrete pavements, and it also reduces material and construction variability. Further, precast concrete pavement systems allow the cost-effective implementation of certain sustainability features, including enhanced aesthetics, specialty surface textures, high surface reflectivity, and photocatalytic materials. Many of these features are made possible because the pavement wearing surface can be cast against a mold in two (or more) lifts if desired, giving a degree of control that is not possible with cast-in-place pavements. Casting the surface against a mold also results is a denser surface, as the lighter concrete mixture constituents (air and water) rise towards what will be the underside of the pavement and the dense cement and aggregate settle to form a dense molded surface.

Initial work in this area focused on the use of precast panels to rapidly install full-depth repairs in jointed concrete pavements (Tayabji and Hall 2008). This repair method continues to be used in a number of states, where full-lane width panels are cast in two to three standard lengths, stockpiled, and then rapidly inserted into a gap cut to the specified size in the damaged pavement; see Figure 3.3.

Current emphasis is on the implementation of precast panels to create entire pavement systems. The following two basic approaches are currently used in the United States (FHWA 2011):

- *Jointed precast concrete pavement system (JPCPS)* – These systems typically consist of rectangular precast panels that are one lane in width, 10 to 15 ft in length, and similar to a conventionally designed concrete pavement in thickness. Although there are multiple variations of this type of system, in one of the most common systems the panels are placed on a meticulously prepared surface with bedding grout used to ensure uniform slab support. Load transfer devices, embedded using non-shrink, high-strength grout inserted after placement, are used to establish composite slab action across joints (Fort Miller Co. 2011).
- *Precast prestressed concrete pavement system (PPCPS)* – These systems typically consist of rectangular precast slabs that are up to two lanes (38 ft) in width, 10 ft in length, and thinner than conventionally designed concrete pavements, with a thickness of 7 to 8 in. for highway applications. They are prestressed in the transverse direction during fabrication and placed in 150- to 250-ft long pavement segments that are post-tensioned longitudinally during construction. Plastic sheeting is used to separate the panels from the base, allowing movement of the panels during the post-tensioning operation. The use of prestressing/post tensioning increases load capacity, maximizing pavement life (Merritt and Tayabji 2009).

Regardless of the system employed, precast pavements have some unique features that can enhance sustainability. First, when used either as a full-depth repair or as an entire pavement system, a well executed precast pavement installation can be done with minimal disruption to traffic because there is no need to wait

Figure 3.3 Precast pavement being installed (photo courtesy of Shiraz Tayabji, FHWA)

for the concrete to gain adequate strength prior to opening to traffic. This is most significant for repairs in urban areas but is also true for full-lane replacements if staged correctly. Minimizing traffic disruption has many positive effects, including reduced user costs incurred due to delay and corresponding increased fuel consumption, reduced environmental damage from increased emission associated with vehicles slowed by congestion, and reduced social impacts to surrounding communities from noise and gridlock.

Second, precast systems are anticipated to have long lives that are relatively maintenance free. The sustainability advantages of long-life pavements have already been discussed in Chapter 2, but in summary they include the following:

- Reduced life-cycle economic cost.
- Reduced life-cycle environmental impact due to less need for extracted materials and for future rehabilitation and reconstruction.
- Reduced traffic delay and congestion during construction and over the life cycle.

The advantages of using two or more lifts and casting the pavement surface against a mold can be capitalized on in precast pavement systems, optimizing the surface for the given application. For a pavement carrying high-speed traffic, the surface can be designed to be exceptionally quiet while providing good frictional characteristics to enhance safety. For slower speed pavements designed for the urban environment, the surface can be designed to be aesthetically pleasing, cool, photocatalytic, and drainable and even to provide a “traffic calming” effect by inducing nuisance vibration in vehicles operating too quickly. Further, precast pavement systems for the urban environment can be designed to “snap in and snap out,” meaning that the precast panel over a needed utility repair is simply detached and removed, the repair to the utility completed, and the panel reattached. This eliminates waste, expedites the repair process, and maintains the integrity of the pavement system. It is easy to envision the ability to design a major urban project, such as an intersection replacement, using a precast pavement system in which all the design, fabrication, and staging are done ahead of time and the work is completed over a few evenings or a weekend.

Roller-Compacted Concrete Pavement

Roller-compacted concrete (RCC) pavement has been used in the construction of various types of civil infrastructure, including dams, other hydraulic structures, cargo handling facilities, and pavements. Although the constituents in RCC are similar to conventional concrete, they differ in proportioning, with RCC typically having less cementitious material and an aggregate gradation similar to that used in hot-mix asphalt (HMA) mixtures. In a fresh state, RCC is very stiff and is thus placed using construction methods similar to those used for HMA construction, using an HMA-type paver and compacted by heavy vibratory steel drum and rubber-tired rollers (Figure 3.4). Ultimate load-carrying capacity is obtained through a combination of internal, aggregate-to-aggregate friction and the cohesion obtained through hydration of the binder. The final surface is adequate for pavements carrying traffic at low and moderate speeds but often is either diamond ground or overlaid to meet the smoothness demands of high-speed traffic. An excellent guide on RCC pavements has been written by Harrington et al. (2010), and additional information is provided by the Portland Cement Association (PCA 2011).

RCC shares many sustainability attributes with conventional concrete pavements, including low life-cycle economic costs, the ability to incorporate a high amount of RIBMs into the mix, and high surface reflectivity. Some of the specific advantages of RCC from a sustainability perspective include low initial cost and rapid construction compared to both conventionally designed concrete pavements and multi-lift HMA pavements of similar structural capacity. In addition, if the lower cementitious content translates into a lower portland cement content, the carbon footprint is

Figure 3.4 RCC pavement being placed (photo courtesy of PCA)

reduced. Load transfer across joints may be lower than conventional concrete because dowels are not used.

As another arrow in the quiver for designers of sustainable concrete pavements, the use of RCC as a paving material will likely continue to grow.

Interlocking Concrete Pavers

Similar to precast concrete pavement systems, interlocking concrete pavers are also produced in a plant, where the material is proportioned, pressed, and cured under controlled conditions, then shipped to the site where they are assembled on grade. Again, fabrication under controlled conditions eliminates a major construction—unfavorable ambient weather conditions—which can play havoc on conventionally cast-in-place concrete pavements, and it also reduces material and construction variability..

Pavers are the original pavement surfacing material, with the use of stone pavers dating back to antiquity. Modern interlocking concrete pavers have evolved to be extremely versatile and durable and are used in projects as varied as low-volume parking areas to the most heavily loaded cargo handling facilities. Figure 3.5 shows an example of permeable interlocking concrete pavers, which not only possess the necessary structural capacity and long-term durability for the application but also are aesthetically pleasing while effectively managing surface run-off. Vehicular interlocking concrete pavers, such as those shown in Figure 3.6, can carry mainline traffic. They are particularly applicable in urban areas where both their attractive appearance and versatility to permit maintenance of underground utilities can be used to good advantage.

Recent innovations have led to the installation of interlocking concrete pavers in Chicago that have a thin photocatalytic surfacing. The high reflectivity of these pavers will help mitigate the urban heat island effect. The photocatalytic surface will help keep the surface bright white while also treating nitrous and sulfur oxides. Automated methods have been developed in Europe that expedite the placement of interlocking concrete pavers, significantly accelerating the construction process. Additional information regarding interlocking pavers, including using them to support sustainable design, can be found at the website of the Interlocking Concrete Pavement Institute (www.icpi.org/).

Thin Concrete Pavement Design

Most of the design technologies discussed so far (e.g., two-lift, precast, pavers, and RCC) have been around for decades and are experiencing something like a revival due to their implications for sustainability. Thin concrete pavement (TCP) design, however, is

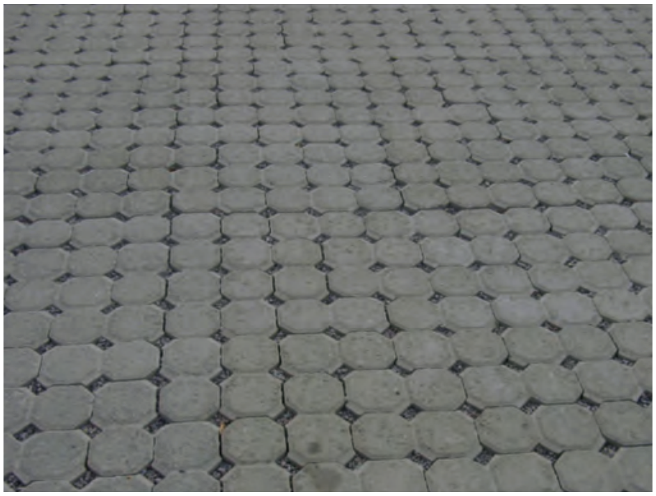

Figure 3.5 Permeable interlocking concrete paver blocks make an aesthetically pleasing, well-drained pavement for low-volume streets and parking lots (photo courtesy of Interlocking Concrete Pavement Institute)

Figure 3.6 Vehicular interlocking concrete pavers being placed in a historic downtown area (note the use of colored concrete to provide a visual offset for the crosswalk) (photo courtesy of Tom Van Dam, CTLGroup)

truly new and has yet to gain widespread acceptance in North America. TCP design originates in Chile (Covarrubias and Covarrubias 2007 and is still under evaluation there as well as in a number of other countries. In North America, considerable work has been conducted at the University of Illinois with very promising results (Cervantes and Roesler 2009).

The basic concept is simple. Stresses are generated in concrete slabs through a combination of traffic and environmental loads. The larger the concrete slab, the more truck axles it will carry at one time and the higher the stress incurred due to temperature and moisture gradients. Over time, the repeated stresses generated by the combination of traffic and environmental loading will result in fatigue cracking of the slab. By reducing slab size to a square with the dimensions of one-half a lane (6 ft by 6 ft), the stresses generated are significantly reduced to the point that slab thickness can be reduced by almost half. The reduction in slab thickness will be accompanied by higher deflections; thus the need for good base support that resists pumping and erosion is emphasized (Cervantes and Roesler 2009).

The promise of TCP design is that the reduction in slab thickness will substantially reduce the economic and environmental costs of concrete pavements. Slab thickness of as little as 4 to 6 inches may be all that is required to carry moderate to heavy traffic volumes, and early results indicate that there is no need for embedded steel load transfer devices.

At this juncture, a number of test sites are being constructed to investigate TCP designs, but a major barrier to implementation is that this is a patented technology, thus giving most DOTs pause in considering it for adoption.

Pervious Concrete

An approach to reducing the amount of water runoff from hard surfaces is to build pervious pavements for parking lots and low speed roadways; see Figure 3.7. Pervious pavements allow water to seep into the ground, thereby recharging groundwater and allowing natural processes to treat it instead of having to build extensive treatment works. This design alternative is discussed in detail in Chapter 9.

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Figure 3.7 Pervious concrete being placed (photo courtesy of John Kevern, University of Missouri-Kansas City)

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Chapter 4

SUSTAINABLE CONCRETE PAVEMENT MATERIALS

Peter Taylor
Tom Van Dam

The materials used in making paving concrete have a significant impact on the sustainability of the pavement. This chapter details the importance of using materials that result in durable, long-lasting concrete that withstands traffic loadings and climate during its service life. The chapter primarily focuses on cementitious materials, because of their environmental impact as part of mixture design. The discussion emphasizes the need to use the appropriate amount of cementing materials by reducing unwarranted cement and using conventional supplementary cementitious materials (SCMs), including fly ash and slag cement. The emergence of lower energy, lower emissions cements, including blended cements, portland-limestone cements, geopolymers, and carbon neutral/sequestering cements, is also discussed. The chapter concludes with a discussion of other concrete ingredients, with specific emphasis on the use of recycled and industrial byproduct materials used as aggregate.

1. Cementitious Materials

It is well established that the manufacturing of portland cement (specified under AASHTO M 85/ASTM C 150) is an energy intensive process, involving heating large quantities of finely ground rocks and minerals to very high temperatures (roughly 1400°C) to produce nodules called clinker that are then interground with gypsum to a fine powder; see Figure 4.1. In addition, the carbon dioxide (CO_2) burden is high because the process includes decomposing calcium carbonate ($CaCO_3$) rock into calcium oxide (CaO) and CO_2. Roughly half of the CO_2 generated comes from this source, and the proportion is increasing as manufacturers make their process more energy efficient (Van Dam and Taylor 2009). The generation of CO_2 through the cement manufacturing process is illustrated in Figure 4.2 (Van Dam et al. 2010).

The amounts of energy required and CO_2 produced depend on the age and efficiency of the manufacturing plant. Many older plants use a wet process that includes drying the materials from slurry. Many of these plants have closed in the United States as a result of economic pressures and because newer, more efficient dry-process facilities have come on line. The FHWA INVEST tool gives credit for cement supplied from efficient Energy Star® plants (see Chapter 10). Approximately 0.8 to 1.0 tons of CO_2 are produced per ton of cement (Hanle et al. ND, Van Dam and Taylor 2009), with the U.S. national average currently listed as 0.927 tons of CO_2 equivalent produced per ton of cement (NREL 2011).

Figure 4.1 A cement kiln (photo courtesy of PCA)

In 2008, the total U.S. greenhouse gas (GHG) emissions were estimated at 7 billion metric tons of CO_2 equivalent, 40 million tons (about 0.6 percent) of which were generated through the manufacturing of portland cement (EPA 2010). This is compared to 5 to 7 percent reported for the rest of the world (Malhotra 2000). The lower figure for the United States reflects the facts that cement manufacturing in the United States is becoming more efficient and that the American way of life generates considerably more CO_2 equivalents in sectors other than cement manufacturing compared to the rest of the world.

Roughly 2.8 billion tons of cement is consumed annually worldwide (WBCSD 2010), which equates to approximately 800 lb of cement per person per year. While the impact tied to manufacturing portland cement is relatively high, it must be remembered that relatively little cement is used in a concrete mixture—normally 12 to 15 percent by mass in pavement mixtures. The other constituent materials (aggregate, water, SCMs, and admixtures) typically have very little energy or CO_2 impact associated with them, thus making concrete a reasonably efficient material as a whole. For example, the 800 lb of cement per person per year discussed previously would make roughly 5,600 lb of concrete, making concrete the most commonly used building material on the planet with only water being used in greater amounts. Concrete is literally the foundation upon which modern civilization is built.

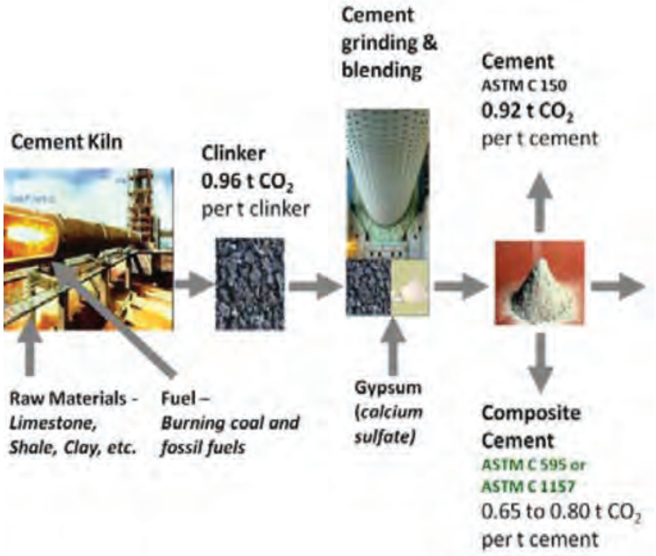

Figure 4.2 CO_2 generation in cement manufacturing (Van Dam et al. 2010)

Work is ongoing to quantify the life-cycle environmental impact of pavement materials, including concrete (MIT 2010).

Although the global impact of cement manufacturing on GHG emissions is large, it must be remembered that the burdens can be reduced by any combination of four actions:

- Reduce the energy and GHG emissions associated with portland cement clinker production.
- Reduce the amount of portland cement clinker in the cement.
- Reduce the amount of cement in the concrete mixture.
- Use concrete more efficiently in a pavement over the life cycle.

Each of these is discussed in following sections.

More Efficient Clinker Production

The manufacturing process for cement is continually being improved and made more efficient by the use of more efficient kilns, more efficient grinding equipment, optimized transportation, and modified process control. The use of alternative fuels including tires and bio-fuels helps reduce the combustion of nonrenewable resources while removing them from the waste stream (PCA 2009). Burning hazardous organic waste such as solvents and oils in cement kilns is beneficial not only because it reduces the amount of fossil fuel combusted but also because the extremely high temperatures decomposes them completely, rendering them non-hazardous (Basel Convention 2009).

Another approach to reduce consumption of nonrenewable resources while reducing waste destined for landfills is the use of industrial byproducts such as fly ash (Bhatty, 2006), foundry sand, slag, mill scale, and cement kiln dust as raw feed.

Work is ongoing to identify means of making cement manufacturing more efficient by modifying its molecular composition. This work is likely to take several years to find its way into everyday practice.

Reducing Portland Cement Clinker in Cement

Reducing the portland cement clinker content in the cement directly reduces the GHG emissions and energy consumption associated with cement manufacturing. Portland cement can be supplemented in concrete mixtures with the use of so-called supplementary cementitious materials (SCMs) and/or with finely ground limestone. SCMs are largely byproducts from other industries, such as the burning of pulverized coal at power plants or the production of iron from ore in a blast furnace, but can also be produced from natural materials such as clay. These processes also result in GHG emissions and energy consumption but at lower rates than clinker production.

SCMs chemically and physically complement the hydration of portland cement, often resulting in more durable concrete. Hydration of portland cement produces calcium silicate hydrate (C-S-H) that provides the backbone of strength and impermeability of the cementitious system. But portland cement hydration also produces calcium hydroxide (CaOH), a crystalline material; see Figure 4.3. Calcium hydroxide contributes little to strength or impermeability. Most SCMs contain glassy silica and aluminate phases that react with the calcium hydroxide to form more C-S-H and/or calcium silica aluminate hydrate (C-S-A-H), enhancing the long-term performance of the concrete mixture. The types of commonly used SCMS are discussed in more detail in a later section.

Figure 4.3 Scanning electron micrograph of C-S-H and CaOH crystals (Kosmatka and Wilson 2011)

One or more SCMs can be included in the cement by inter-grinding with the clinker or by blending with cement at the cement plant, in which case they are sold as blended cements under AASHTO M 240/ASTM C 595. Alternatively, it is common to blend the SCMs with the cement and other concrete ingredients at the batch plant.

Under existing U.S. standards for plain portland cement (AASHTO M 85/ASTM C 150), the system may contain up to 5 percent ground limestone as well as up to 5 percent inorganic processing additions. In practice, the amount of ground limestone and inorganic processing additions are less, limited by the loss-on-ignition (LOI) requirement. The standards impose limitations to ensure that the performance of such materials is not reduced. Consideration is being given to increasing the amount of permitted ground limestone as in Canada and Europe (Hooton et al. 2007).

Specifications exist for both blended and performance cements (Van Dam and Smith 2011). Blended cements are described under AASHTO M 294/ASTM C 595, which impose limits and requirements on the source and performance of all of the ingredients. These cements are a blend of portland cement and one or more SCMs. Ternary cements containing two SCMs can also be created at the batch plant by blending more than one SCM, a practice often used to address side effects of one SCM through the inclusion of another SCM. Extremely efficient mixtures can be prepared using such systems (Tikalsky 2007). However, it has been noted that batch plant–created ternary mixtures require expertise and close attention to detail, dictating the need for a high level of quality control.

In addition to blended cements, ASTM C 1157 is a “performance” standard for hydraulic cements that has no requirements regarding the composition of the cement but instead imposes performance limits. ASTM C 1157 cements with 10 percent limestone have been produced and used successfully on pavement projects in several states (Hooton 2009, Van Dam et al. 2010).

Reducing Cementitious Contents in Concrete

Many specifications require that a minimum amount of cementitious material (or portland cement) be used in paving concrete (e.g., a traditional concrete paving mixture may require a minimum six-sack mix, which is equivalent to 564 lb/yd^3 concrete). This minimum cement content requirement may have been appropriate before the common use of chemical admixtures and the adoption of optimized aggregate grading, but may no longer be relevant using today’s concrete and paving technologies.

Performance of a mixture is fundamentally controlled by the water-to-cementitious-materials (w/cm) ratio as long as there is sufficient paste in the mixture to fill the voids between the aggregate particles and to separate the aggregate particles so that they will flow past each other in the fresh state. However, workability can be improved with the use of admixtures, within limits, and by reducing paste demand through use of an optimized aggregate gradation that contains coarse, intermediate, and fine particles (Taylor et al. 2006). As long as the concrete is workable and is placed with good consolidation, long-term performance will generally be improved by reducing the cementitious content. This means that paving mixtures can be made with lower cementitious contents than the traditional six-sack concrete mixture without compromising engineering performance. Education, investment in additional aggregate bins, and improved quality assurance may be necessary to reduce the risk of failures.

Reduce Concrete Used Over the Life Cycle

All things equal, sustainability is improved by reducing the amount of concrete used for a given application. But it is essential that this is considered over the life cycle of the pavement, and not just in the short term. Two essential elements to accomplish this are appropriate design (as discussed in Chapter 3) and the use of durable concrete materials.

With regards to the former point, there is short-term economic and environment-related pressure to reduce the thickness of concrete pavements, lowering both the initial cost and the environmental footprint. The use of improved design methodologies and appropriate design details (e.g., proper joint spacing, load transfer devices, quality base, and so on) can accomplish this without compromising long-term structural performance. But it is essential that this be done with caution, as thickness correlates with structural capacity, and arbitrarily using thinner concrete will likely compromise one of the benefits of using a concrete pavement, which is the potential to provide many years of low-maintenance service. Specifying a concrete thickness insufficient to carry traffic over the design life can have large negative impacts on sustainability (economic, environmental, and social), not only because the pavement will need to be replaced sooner than anticipated but also because of traffic delays during repeated repair and reconstruction. The counter to this is that innovative design may result in significantly improved sustainability even if the short-term initial economic and environmental costs are slightly higher. This is why it is essential that a life-cycle approach be taken when evaluating design changes.

One of the hallmarks of concrete pavement is its legendary longevity. It is reasonable to assume that a properly designed concrete pavement will meet or exceed its design life. It is also known that pavements can prematurely fail even if they are structurally adequate. To address this, in addition to proper design, all the other stages—material selection, construction, and maintenance—have to be adequate and appropriate to ensure longevity. From a cementitious materials perspective, it is paramount that the right materials are selected and proportioned correctly for the environment to which the pavement will be exposed (Taylor et al. 2006). Other factors that need to be considered are the effects that the cementitious materials selection will have on the surface characteristics of the pavement leading to changes in reflectivity, which contributes both to the albedo (e.g., urban heat island effect) and night-time safety as discussed in Chapter 9.

2. Supplementary Cementitious Materials

As discussed above, most SCMs are byproducts from other industries that beneficially react with portland cement to enhance the performance of concrete. The effective use of SCMs reduces not only the amount of portland cement required but also the need to dispose of what otherwise would be industrial waste.

The two most commonly used SCMs in paving concrete are fly ash and slag cement.

Fly ash is a byproduct of burning pulverized coal for the generation of electrical power. The rock embedded in the coal melts in the furnace and is carried up the stack in the flue gases. As it rapidly cools, small glassy spheres are formed that are collected before the flue gases are emitted to the air; see Figure 4.4. Because of the small size, glassy form, and chemical composition of the ash, it dissolves and reacts with the cement paste to contribute to the performance of the mixture. About 63 million tons of fly ash were produced in the United States in 2009, of which about 12 million tons were used either to make cement or in concrete (ACAA 2009).

Fly ash is currently specified in AASHTO M 295/ASTM C 618 in two classes based on the chemical composition. The differences are generally influenced by the source of the coal. In general, Class C fly ash is higher in lime content (CaO) and tends to be more reactive at early ages than Class F. The higher CaO content is beneficial for early strength gain but can have negative effects on alkali-silica reactivity and sulfate resistance. It should be noted that the specification for fly ash is broad and that two ashes from different sources, albeit of the same class, are likely to perform very differently; therefore, performance testing should be conducted to determine if the chosen fly ash is behaving as desired (Taylor et al. 2006).

Dosage of fly ash is typically between 15 and 40 percent by mass of cement. The amount of fly ash that can

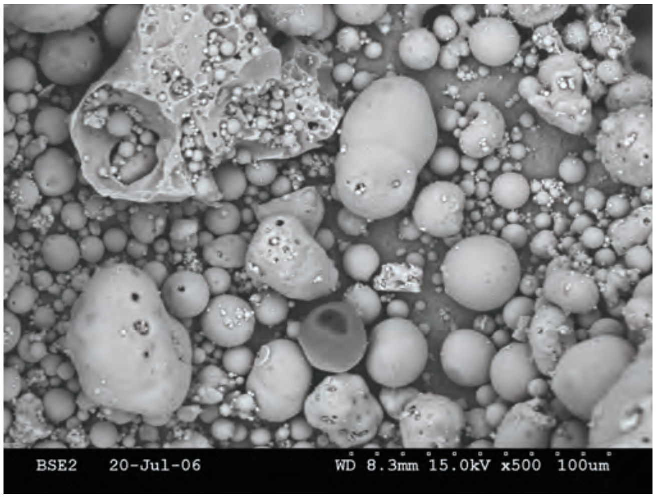

Figure 4.4 Backscatter electron image of fly ash particles (Kosmatka and Wilson 2011)

be used is often limited by concerns of delayed setting times and lower early strength gain. In some cases, there may be a potential for undesirable incompatibilities and a perceived increase in the risk of salt scaling (Taylor et al. 2006). Judicious increases in dosage can be accommodated with attention to detail in mix proportioning and construction workmanship. Local sources will often dictate the availability of acceptable fly ash within a market.

Work is ongoing to find alternative methods to characterize fly ash so that mixture performance can be better predicted.

Slag cement, formerly known as ground granulated blast furnace slag (GGBFS), is the material left after extraction of iron from iron ore; see Figure 4.5. When quenched from the molten state and ground to the fineness of cement, it is an extremely effective SCM. Slag cement is specified by ASTM C 989, and about 3 million tons are used in concrete in the United States every year (SCA 2011). It is generally used in pavements in dosages up to 50 percent but is limited by concerns of early strength gain, especially when placed during cooler ambient temperatures, and scaling resistance. As with fly ash, usage tends to be regional because of limitations on the cost effectiveness of transporting it long distances.

Figure 4.5 Petrographic optical micrograph of slag cement particles (image courtesy of CTLGroup)

3. Emerging Cementitious Systems

Work is ongoing in many institutions looking at non-portland cement based binders (Taylor 2010). Investigations include the use of geopolymers (Van Dam 2010) and alkali-activated fly ash products as well as materials fabricated using waste materials. These are reported to carry significantly lower carbon and energy burdens than portland cement while providing equivalent or superior performance. Some new cements even claim to consume CO_2 in manufacture (FHWA 2010). Many systems have been patented, but they are generally difficult to produce and work with. There are also safety risks associated with some systems that require the use of a highly alkaline activating solution. Some systems may also require more processing, resulting in increased energy consumption. Significant barriers to the use of these materials are as follow:

- Portland cement is inexpensive and robust
- Practitioners are often resistant to change.

Future work on cementitious materials will likely include finding alternative sources of raw materials that will not involve the decomposition of carbonate but rather use calcium-rich industrial byproducts, or possibly shifting away from the use of calcium-based cements entirely and perhaps using magnesium-silicate raw materials.

The anatase form of titanium dioxide has been known for decades to have the ability to keep surfaces clean. A cement containing this compound is now available, although it is more expensive than normal portland cement. Titanium dioxide photocatalyic cements reportedly can break down the harmful compounds of nitrogen oxides (NOx) (Chen and Poon 2009). These systems have been used in Europe, and trials sections are being installed in the United States.

4. Aggregates

Aggregates comprise the bulk of the volume of a concrete mixture. Important aggregate characteristics are gradation, type/source, and durability.

Gradation

Aggregates are often classified by particle size, being normally defined as "coarse" and "fine" split at the No. 4 (0.187 in. [4.75 mm]) nominal sieve opening. This split is used to reduce the risk of segregation of the material in stockpiles. Ideally the aggregates in a concrete mixture should be composed of optimized, well graded particle sizes representing the range of sieve sizes (Taylor et al. 2006). This does not mean that good concrete cannot be made with less than ideal aggregate gradations, but the probability of success is increased with improved aggregate systems.

If necessary, multiple aggregate stockpiles representing different sized materials should be blended to create the desired aggregate grading. This, and the use of as large a nominal maximum aggregate size as practical for a given situation, will allow the reduction of the amount of cementitious materials required in a mixture as shown in Figure 4.6, thus reducing costs and environmental impact.

Aggregate Type

Natural

Natural aggregates, often referred to as pit-run gravels, are extracted from river beds or pits with minimum crushing or processing. They tend to be of a mixed geological composition because they have been transported some distance by natural forces. Energy and CO_2 burdens associated with obtaining and processing these materials are minimal because of the limited amount of processing required. In some cases washing is required to remove clayey dust, with the attendant use of water which will have to be treated.

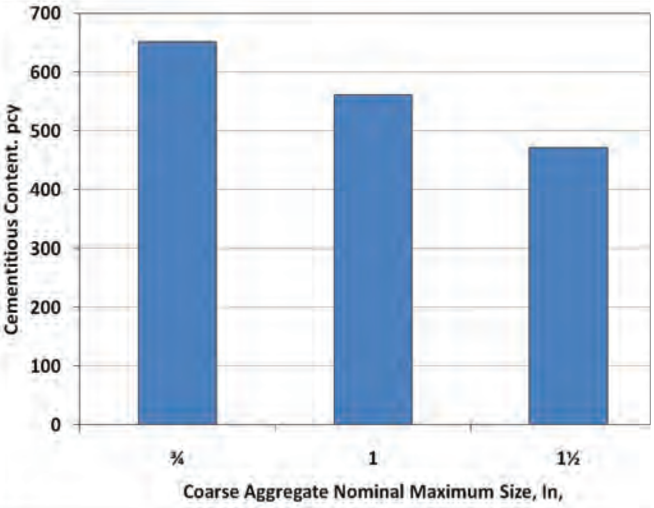

Figure 4.6 Reduction of cementitious content with increasing coarse aggregate size (based on ACI 211)

Sources of high-quality natural aggregates are being depleted, leading to the need to consider whether the current specification requirements (AASHTO M 6 and M 80/ASTM C 33) are overly restrictive or to find methods to beneficiate unacceptable materials.

Natural aggregate particles tend to be rounded and smooth from tumbling in rivers or glaciers, producing good workability of the mixture but potentially reducing flexural strength; see Figure 4.7.

Crushed

In locations where suitable natural aggregates are not readily available, aggregate can be mined from bedrock then crushed and sieved to suitable sizes; again, see Figure 4.7. Generally the dust in these aggregates is not clayey, and therefore higher quantities of material passing the #200 sieve can be accommodated. Additional energy consumption and emissions are associated with mining and crushing activities to obtain these materials. The selection of crushing equipment can influence the shape of the aggregate particles, and care should be taken to avoid systems that produce

Figure 4.7 Rounded (left) and crushed natural aggregates (photo courtesy of Portland Cement Association)

narrow, flaky, or elongated particles, as these will negatively impact workability and have a tendency to fracture during processing.

The workability of mixtures made with crushed materials is generally lower than in mixtures with rounded aggregates, meaning that additional paste may be required to achieve workability. On the other hand, flexural strengths are normally higher.

Light-Weight Aggregates

Light-weight aggregate (LWA) is normally a manufactured product, made by heating shale, clay, or slate in a rotary kiln to about 2000°F; see Figure 4.8. The final product is ceramic in nature and contains controlled amounts of air bubbles, thus increasing aggregate porosity and reducing density. Energy is required to produce LWA. However, benefits have been reported (in reduced cracking risk from internal curing) from the use of a LWA as a portion of the fine aggregate (Henkensiefken et al. 2009). Further, for structural applications, the lighter weight will result in a reduction of the structural members, meaning less concrete will be required. LWA coarse aggregates are not commonly used in pavements.

Recycled and Industrial Byproduct Materials

There is increased interest in recycling concrete and other construction waste for use as aggregates in paving concrete and supporting layers. This is beneficial because it reduces the demand for virgin aggregates and also reduces the need to place the waste materials into landfills.

Figure 4.8 Light-weight fine aggregate (image courtesy of Buildex)

In pavements, the most common application for recycled materials is in the subbase or base layers. This can be achieved in-situ using mobile crushing equipment, significantly reducing transportation costs and environmental impact (Meijer 2008). If recycled materials are used in concrete, the mixes have to be proportioned and tested in the lab to ensure that setting times and strengths are satisfactory. Consideration should also be given to why the original pavement failed; recycled concrete containing alkali-reactive aggregates or aggregates prone to D-cracking may not be advisable for use in paving concrete unless mitigated.

The most common industrial byproduct material used as aggregate is air-cooled blast furnace slag (ACBFS) which is produced from the iron blast furnace. This material has been used in supporting layers and as aggregate in paving concrete. Work currently being conducted for the Federal Highway Administration (FHWA) suggests that if ACBFS is used in paving concrete, special design and construction considerations must be followed to ensure acceptable performance (Morian et al. 2011). Extreme caution must be exercised if other sources of slag (e.g., steel furnace) are being considered for use, as cases of extreme instability and volume change have been reported in some instances, which will lead to rapid pavement failure.

Other uses of recycled materials are discussed in Chapter 8.

Durability

In general, aggregates have limited direct impact on the durability of a mixture unless they are susceptible to D-cracking or are reactive, which are serious issues, or are easily polished.

D-cracking is a problem where aggregates with relatively high-porosity and low permeability tend to absorb water that expands when it freezes, causing the aggregate to fracture and the concrete to crack. It is a regional problem, most common in the Midwest from Kansas through southern Michigan and into

Ohio, in that aggregates prone to D-cracking tend to come from a given geological form. Aggregates that are prone to this should not be used if possible. If they must be used, the susceptible aggregates should be crushed to maximum size of 0.5 to 0.75 in. and blended with larger, non-susceptible aggregates. This will require that in some locations aggregates will need to be imported, with the attendant fuel load. Research is needed to find methods to prevent prone aggregates from expanding or to find applications where they can be safely used.

Alkali-silica reactivity (ASR) is a chemical reaction between certain siliceous minerals within aggregate that react with alkali hydroxides in the concrete pore solution, forming a gel that expands when it imbibes water causing the concrete to crack. Almost every state in the United States has reactive aggregates. Work is ongoing to develop rapid, reliable tests to assess reactivity of aggregates and mixtures and to find ways to prevent their expansion. Use of certain SCMs, particularly Class F fly ash and slag cement, are known to be effective at mitigating expansion and damage from the use of susceptible aggregates. Lithium nitrite is also known to be an effective additive. See AASHTO PP 65-10, *Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*, for recommended testing protocols and mitigation strategies.

Alkali-carbonate reactivity (ACR) is a rare deleterious reaction between certain dolomitic limestone of a very specific microstructure and hydroxyl ions in the concrete pore solution. The reaction is not perfectly understood but likely involves both the expansive formation of brucite (magnesium hydroxide) and the dissolution and swelling of clay phases within the aggregate. Alkali-carbonate reactivity is very damaging, and there is no effective mitigation strategy; thus, susceptible aggregate must not be used. See AASHTO PP 65-10, *Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*, for recommended testing protocols.

Polishing is the tendency of an aggregate at the pavement surface to become smooth under the action of traffic, leading to a reduction in skid resistance. Some states resort to limiting the amount of calcareous materials in their aggregates to limit this effect, although many states must use these materials because of their abundance and lower risk of alkali-silica reaction. In such cases, surface texturing becomes increasingly important to maintain skid resistance.

5. Water

The amount of mix water in paving concrete is primarily governed by the w/cm ratio and paste requirement of the aggregate system and the type and dosage of the chemical admixtures in use. The presence of SCMs will normally reduce the amount of water needed for a given cementitious content. Therefore, choosing a good aggregate system, reducing the cementitious content (within limits), and using water-reducing admixtures will all help to reduce the amount of water required to achieve a given workability. There is normally more water in a typical paving mixture than is required to hydrate all the cement. Typically added water accounts for about 6 percent of the mass of a mixture.

The quality of the mix water is normally not much of a concern. Water that is potable is considered acceptable for use in concrete. Water contaminated by organics and sugars will tend to delay setting and may reduce early strengths. Grey water or water that has been recycled at a batch plant may accumulate dissolved solids, sulfates, and chlorides that may affect mixture performance and durability. Therefore, wash water used to clean tracks and equipment, as well as water recycled from returned trucks, should be processed to remove solids and organics before it is released to the environment or before it is re-used in a batch plant. ASTM C 1602 provides some limitations on the quality of mix water, particularly recycled water and wash water.

Two other significant uses of water at a construction site are for achieving the appropriate moisture content to facilitate densifying soil and unbound granular materials and for dust control. The amounts of water used should be balanced between the needs to achieve engineering requirements and to minimize waste. Dust control on unpaved surfaces can be enhanced by the use of calcium chloride.

6. Admixtures

Chemical admixtures are a common constituent in modern paving concrete, being added to modify one or more of the fresh or hardened properties of the concrete. Chemical admixtures are typically used in pavement mixtures to entrain air, increase workability, and/or control time of setting. Admixtures are used in small dosages and usually comprise less than 0.2 percent by volume of concrete.

Common chemical admixtures are specified using AASHTO M 154/ASTM C 260 and AASHTO M 194/ ASTM C 494. The basic ingredients used in water-reducing and retarding admixtures are sugars and lignosulfonates obtained from corn or wood. The most common accelerating admixture is calcium chloride, although non-chloride based accelerators are also available. The primary materials used in modern high-range water-reducing admixtures (HRWRA) are polycarboxylate ethers and polyvinyl copolymers synthesized from oil-based materials.

Water-reducing admixtures (WRAs) are primarily used to reduce the amount of water required in a mixture to achieve a given workability. For a mixture with a fixed w/cm ratio, water reducers can be used to reduce the amount of cementitious material required, leading to significant savings in cost and environmental impact. They also permit use of lower w/cm ratios in mixtures, leading to improved durability and longevity.

Air-entraining admixtures (AEAs) are used to develop a system of small air bubbles to increase the resistance of critically saturated concrete to deicer salt scaling and cyclic freezing and thawing, increasing longevity of the pavement; see Figure 4.9.

As previously mentioned, lithium-based admixtures can be used to mitigate alkali-silica reaction.

7. Reinforcement

Dowel bars, tiebars, and reinforcement may be used in concrete pavements to help the concrete carry tensile stresses and/or to transfer loads across joints. The most common reinforcement material is steel, and the energy requirement to process steel is high. Dowels and tiebars are used in small quantities, but the amount of steel used in continually reinforced concrete pavements (CRCP) can be significant; therefore, the designer must balance the environment and cost impacts of including the steel with the improved longevity of the pavement.

Dowel bars (smooth bars), or simply dowels, are placed in concrete across transverse joints to provide vertical support and to transfer loads across joints. Dowel bars are typically used on heavy truck routes. Dowel bars reduce the potential for faulting, pumping, and corner breaks in jointed concrete pavements (Smith et al. 1990, ACPA 1991).

Tiebars (deformed bars), or rebar, are placed across longitudinal joints on centerlines or where slabs meet. Tiebars prevent faulting and lateral movement of the slabs and assist with load transfer between slabs. Tiebars are also used to connect edge fixtures such as curbs and gutters to the pavement.

Reinforcement may be used in concrete pavements to improve the ability of concrete to carry tensile stresses and to hold tightly together any random transverse cracks that develop in the slab; see Figure 4.10. Generally, cracking in jointed concrete pavements is controlled by limiting the spacing between joints. When the concrete slab is reinforced, joint spacing can be

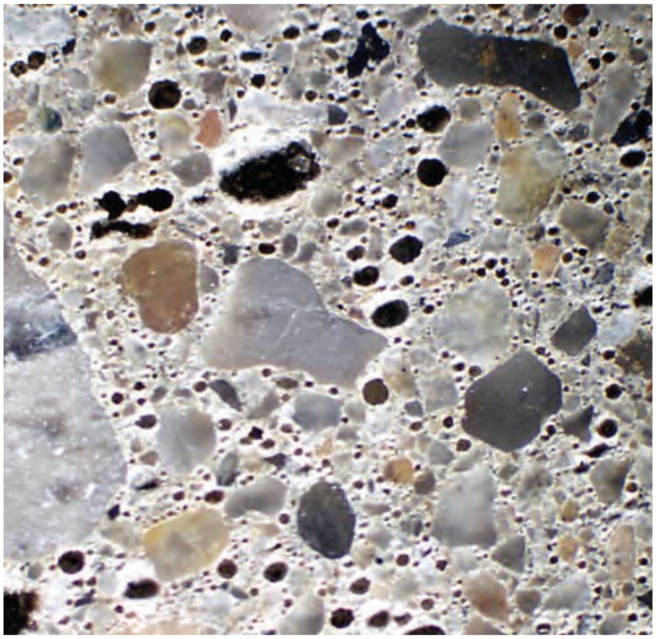

Figure 4.9 Air-entrained concrete (image courtesy of CTLGroup)

increased. The most common reinforcement is embedded steel placed either as welded wire fabric or as reinforcement bars. Fiber-reinforcement can also be used. Fibers are commonly composed of steel or polymers, although various other materials (e.g., carbon, cellulose, glass, and so on) have been used.

8. Proportioning

The aim of mixture proportioning is to find the combinations of available and specified materials that will ensure that a mixture is cost effective and meets all performance requirements. In the case of sustainable design, minimizing the pavement's environmental footprint (e.g., embodied energy and GHG emissions) over the pavement life cycle must be one of the performance requirements.

The freedom to vary mixture proportions depends on the specification. There is a movement to write specifications that are less "recipe" based and more focused on the desired performance. This places decision making, and risk, in the hands of the concrete provider and paving contractor, with the attendant economic and environmental impacts. Such a trend will mean that everyone in the process has to be better educated about the broad impacts of their decisions.

Ideally a concrete paving mixture will use an optimized combined aggregate gradation that minimizes voids and thus the paste requirement, resulting in minimal cement and water required. Achieving this should not be at the expense of significantly increased processing or transportation impacts.

Figure 4.10 Reinforcing for CRCP (photo courtesy of Mike Ayers, American Concrete Pavement Association)

Aggregates should be resistant to the environment and not prone to D-cracking, ASR, or ACR. Cementitious content should be kept as low as possible without compromising mixture performance, both in the fresh and hardened state. The selection of the cementitious system should be to maximize SCM contents while preventing ASR, resisting freezing and thawing distress, and meeting other specified requirements. The quality of the paste, including the w/cm ratio and air-void system, should be selected based on the environment to which the mixture will be exposed.

Guidelines for achieving these objectives are available in *Integrating Materials and Construction Practices for Concrete Pavements* (Taylor et al. 2006).

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Chapter 5

CONSTRUCTION

Gary Fick

Duration of the construction phase is relatively short compared to the total life of a concrete pavement. One might assume, therefore, that the potential for sustainability improvements during the construction phase is limited. In fact, the opposite is true: A large contributor to a concrete pavement's sustainability is its long service life, which is directly related to initial construction quality. Efforts to enhance sustainability through optimized design and material selection can be negated through improper construction processes and/or a lack of quality control; see Figure 5.1.

After a brief overview of sustainability issues related to concrete pavement construction, this chapter discusses how these issues can be addressed during the various phases of a traditional, slipform paving construction project. The chapter ends with brief discussions of other construction methods and their potential for enhancing pavement sustainability.

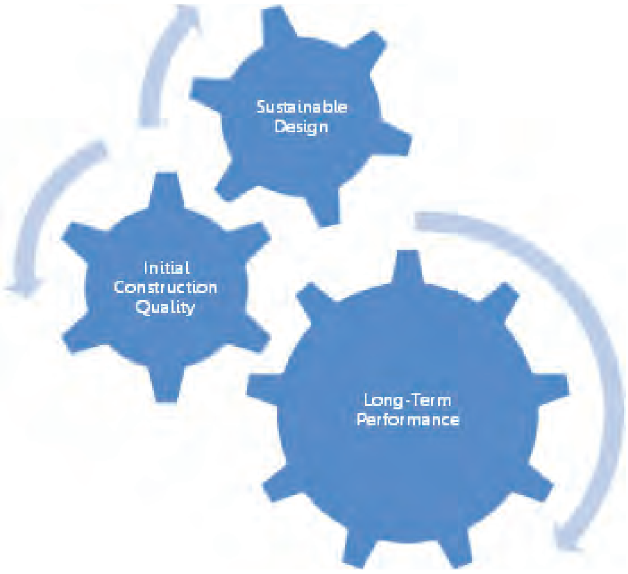

Figure 5.1 Initial construction quality helps realize the designed long-term performance (image courtesy of Gary Fick, Trinity Construction Management, Inc.)

1. Overview of Construction Issues Related to Sustainability

In addition to implementing proper construction and quality control processes that ensure a durable, long-life pavement, maximizing pavement sustainability during the construction phase involves addressing immediate environmental and societal impacts of construction. These include the following:

- Erosion and storm water runoff
- Emission of greenhouse gases and particulates through equipment exhaust stacks
- Generation of airborne dust particulate from construction processes
- Noise generated from construction processes
- Increased road user cost due to traffic delays caused by construction

To address both the short- and long-term impacts of the construction process on pavement sustainability, three categories of activities should be emphasized:

- Reducing construction-related waste and disruption to the surrounding area
- Optimizing equipment for maximum fuel efficiency to minimize both consumption and exhaust emissions
- Constructing durable concrete pavements as indicated by the following characteristics (specifications will vary by agency):
  a. Optimized paste content
  b. Low permeability
  c. Adequate entrained air
  d. Strength and thickness as specified
  e. Uniform mixture properties (within batch and between batches)

In most cases, these issues are addressed as a matter of practice, as contractors are concerned with maximizing efficiency and minimizing costs. The rest of this chapter outlines specific considerations related to these activities in all the phases of construction. Table 5.1 summarizes concrete pavement construction practices that can lead to improved sustainability.

It should be noted that discharge of materials from a roadway construction project is regulated by federal law and enforced individually by each state. Regulations and mitigation measures are ever changing and apply equally to all types of roadway construction projects. There are no specific measures for concrete pavement projects that differ from other types of roadway construction. Therefore, this facet of environmental impact is not addressed specifically in this chapter. Readers should fully inform themselves of the appropriate statutory regulations regarding the discharge of erodible materials and sediment from a project site.

2. Traditional Slipform Paving Processes and Impacts on Sustainability

In this section, sustainability-related factors and suggestions are provided to manage the economic, environmental, and social impacts of various slipform pavement construction processes.

Establishing and Operating a Plant Site

Typically, for projects over 10,000 yd^3 a dedicated concrete plant is mobilized. Doing so requires that a plant site be selected and stripped of vegetation and topsoil. The site may be chemically stabilized and/or plated with granular material to minimize pumping soil into the aggregate stockpiles and to provide a more weatherproof hauling surface for trucks.

Managing Economic Impacts

- First, locate the plant site to minimize the average haul distance for the concrete.
- Second, locate the site to minimize the haul distance from the supplier's point of distribution for aggregate material, which comprises the largest volume of the concrete mixture.

Managing Environmental Impacts

- Storm water runoff and washout water/sediment should be contained and/or filtered to prevent contamination of local waterways (local statutory requirements apply).

- A combination of granular materials, such as recycled pavement materials, and water sprinkling should be used for dust control.
- Tracking mud onto public roadways should be controlled through the use of a stabilized construction entrance. Portable wheel wash systems may be necessary and/or required in some jurisdictions.
- Plant sites should be re-vegetated as soon as practical after construction to prevent detrimental runoff.
- Avoid extended idling of diesel-powered equipment to reduce greenhouse gas emissions.

Managing Social Impacts

- Public rights of way owned by the agency should be made available to the contractor for use as plant sites and borrow sources whenever possible to minimize impacts on the public.
- The plant site should be located far enough from residential areas that noise and dust can be mitigated to a level that is not objectionable.
- Utilize brownfield sites whenever available and economically feasible.

Stockpiling Aggregate

Aggregates are typically stockpiled using front-end loaders (Figure 5.2) or radial stackers (Figure 5.3). Either method is acceptable from a quality standpoint as long as segregation is prevented. Segregated aggregate can lead to non-uniformity during concrete production, which will reduce long-term performance.

Managing Economic Impacts

- Radial stackers typically conserve energy when connected to an existing power grid, due to more

Table 5.1 Summary of Concrete Pavement Construction Practices That Enhance Pavement Sustainability

Construction Practice	Sustainability Benefits
Providing a uniform concrete mixture that meets specifications	• Enhanced long-term pavement performance • Smoother pavements, which result in improved fuel efficiency and reduced vehicle maintenance costs for the traveling public
Placing dowels, tiebars, and reinforcing in the proper location	
Using proper finishing techniques	
Constructing smooth pavements	
Ensuring timely and effective curing of the concrete pavement	
Using alternative fuels	• Reduced greenhouse gas and particulate emissions • Utilization of fuel generated from renewable sources
Reducing idling of diesel engines	
Using equipment that meets or exceeds EPA emission requirements	
Allocating equipment resources wisely by matching the quantity and size of equipment to project needs	Improved energy efficiency
Implementing appropriate erosion control measures	Preserved water quality in surrounding bodies of water
Containing washout sediment	
Optimizing plant site location with respect to the average haul distance for concrete and delivery of raw materials	Reduced fuel consumption
Properly constructing and maintaining haul routes	
Water sprinkling of haul routes and plant sites for dust control	Control of objectionable airborne particulates
Recycling washout water	Conservation of water
Stabilizing construction entrances where construction traffic enters public roadways	Mitigation of sediment runoff
Using public rights of way for plant sites, staging areas, and borrow sources	Minimized environmental impacts on private property
Mitigating construction noise from exhaust stacks, banging tailgates, plant site operations, and sawing	Reduced negative impacts on the neighboring communities
Considering traffic delays when planning project staging and logistics	Reduced road user costs caused by delays
Implementing accelerated construction methods that result in reduced construction durations and earlier opening of facilities	
Constructing subgrade and subbase(s) to tighter tolerances	Reduced concrete waste and enhanced probability of achieving smooth pavement
Texturing	Enhanced safety through proper friction characteristics and reduced tire-pavement noise

efficient burning of fuel used in commercial generation of electricity.

- Front-end loaders may be the preferred option when radial stackers are powered by an on-site generator that is not being utilized for other plant site activities.

Managing Environmental Impacts

- All equipment (generators, front-end loaders) should conform to EPA requirements, and the use of alternative fuels should be considered whenever economically feasible, to reduce GHG and particulate emissions from diesel exhaust.
- Radial stackers connected to an existing power grid likely result in fewer emissions due to more efficient burning of fuel used in commercial generation of electricity.

Managing Societal Impacts

- Noise and dust from the plant site should be mitigated through proper site selection and sprinkling.

Establishing and Maintaining Haul Routes

In most cases, haul routes are constrained by construction staging and the maintenance of traffic. The primary sustainability-related issue that should be considered is preparing and maintaining the haul route in a smooth and stable condition. Fuel efficiency of the haul units will degrade on soft/yielding haul routes. Rough haul routes will lead to an increase in repairs and maintenance to the haul units. Extremely rough haul routes can cause the mixture to segregate when non-agitating trucks are used.

Managing Economic Impacts

- Fuel efficiency is affected by haul route stability. Temporary haul routes may be stabilized with recycled materials that can be re-used in later phases of the project.
- Haul routes should be maintained in a condition that will reduce the occurrence of unnecessary vehicle repairs and maintenance.
- Maintaining the haul routes in good condition will also reduce the average cycle time for concrete delivery, thus requiring fewer trucks and reducing the quantity of fuel used per cubic yard of concrete.

Managing Environmental Impacts

- Dust should be controlled by sprinkling the haul route with water.
- Tracking mud from the haul route on to public roadways should be minimized by constructing stabilized construction entrances.

Managing Societal Impacts

- Locations where haul units exit and enter public roadways should be monitored to reduce traffic delays experienced by the public.
- Excessive noise generated by haul units (exhaust stack, banging tailgates, etc.) should be remedied.

Concrete Production

Recommendations regarding materials and proportioning of concrete mixtures from a sustainable perspective are addressed in Chapter 4. Once a mixture has been optimized with regard to sustainability, the concrete production process should be monitored and adjusted as needed to achieve the desired results.

Figure 5.2 Front-end loader used for stockpiling aggregate (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Figure 5.3 Stockpiling aggregate with a radial stacker (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Concrete used for pavement is produced at either a central mix plant (Figure 5.4) or a dry batch plant utilizing transit mix trucks (Figure 5.5). Regardless of the equipment used, it is imperative that the plant produce a concrete mixture that meets or exceeds specification requirements, is uniform within each batch, and is also uniform from batch to batch. Non-uniform concrete leads to non-uniform performance, which in turn results in premature failure with related maintenance and rehabilitation costs.

Non-uniformity of the concrete mixture can also lead to wasted materials, because the concrete producer is forced to use more cementitious material to consistently meet specifications. A preferred approach is to implement quality assurance procedures that will improve uniformity and lead to the most efficient use of materials.

Most concrete plants utilized for concrete paving projects are equipped with automated batching controls. While this certainly improves productivity, it is no guarantee that quality is improved. Attention to details is required.

Figure 5.4 Central mix concrete plant (photo courtesy of Jim Grove, FHWA)

Figure 5.5 Ready mix concrete plant (photo courtesy of Jim Grove, FHWA)

In particular, the moisture content of the aggregates should be tested frequently and the mixture proportions adjusted according to the moisture condition of the aggregates being incorporated into the concrete.

Thorough mixing is also necessary. There are many differing specifications regarding mixing time. Mixing for the minimum specified time may or may not produce uniform concrete that meets specification. Each concrete plant and each mixture is unique; mixer uniformity tests (ASTM C 94) should be utilized to determine the minimum acceptable mixing time to produce uniform concrete.

Water is a natural resource that should be conserved. However, conserving water should not come at the expense of dust control or concrete quality (e.g., washing out trucks and cleaning the paver properly). Washout water generated at the concrete plant site should be recycled whenever possible.

The decision about source of water to use on a concrete paving project should be based on three criteria: First, concrete quality. Mixing water should be free of organics that can degrade quality. Second, the environment. The overall environmental impact of various source options should be considered. Because most potable water sources have been treated in some manner, there is an associated energy expenditure that is not necessarily needed for the production of concrete. However, using sources of untreated water (wells, ponds, and streams) may have an adverse impact on the environment. Some environmental compromise is associated with the choice of a water source. Third, economic factors. Costs must be factored into the decision process for choosing a source of water.

Managing Economic Impacts

- Energy efficiency is improved by matching plant production capabilities to the paving operation.
- The production of uniform, high-quality concrete leads to concrete pavements that perform as expected or better than expected; thus, the life-cycle costs of these pavements are lower than for pavements that have premature failures due to quality deficiencies, non-uniformity, or both.

- Quality assurance procedures aimed at improving the uniformity of the concrete reduces cost through the efficient use of material resources.

Managing Environmental Impacts

- Dust collectors on concrete plants should be in proper working order.
- Dust generated by plant site traffic should be controlled by sprinkling with water.
- Quality assurance procedures aimed at improving the uniformity of the concrete ensure the efficient use of material resources.

Managing Societal Impacts

Noise sources at the concrete plant that are a nuisance to neighboring businesses or residences should be mitigated.

Transporting Concrete

Various types of hauling equipment are available for transporting concrete for a paving project. These range from transit mix trucks (Figure 5.6) to tractor-trailer rigs (Figure 5.7). From a sustainability perspective, efficiency should be maximized by matching the type, size, and number of haul units to project constraints (production rate, haul route conditions, maneuverability, etc.).

Haul units must be washed out frequently enough to prevent the build-up of hardened concrete which may eventually break free and be incorporated in the pavement, causing a future pavement failure. (See the discussion of water use in the immediately preceding section.) Washout pits (Figure 5.8) should be designed to control harmful runoff.

Managing Economic Impacts

Haul efficiency should be maximized by matching the type, size, and number of haul units to the project conditions.

Managing Environmental Impacts

- All equipment should conform to EPA requirements, and the use of alternative fuels should be considered whenever economically feasible to minimize emission of GHGs and particulate through diesel exhaust.
- Dust should be controlled by sprinkling the haul route with water.
- Control harmful runoff from washout pits.
- Recycle washout water whenever possible.

Figure 5.6 Transit mix concrete truck (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Figure 5.7 Tractor trailer concrete hauling unit (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Figure 5.8 Washout pit used to clean concrete trucks (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Managing Societal Impacts

- Excessive noise generated by haul units (exhaust stack, banging tailgates, etc.) should be remedied.
- Locations where haul units enter and exit public roadways should be monitored to reduce traffic delays experienced by the public.

Concrete Placement and Finishing

Placing and finishing concrete pavement is a complex process that involves the use of sophisticated equipment in conjunction with the skilled craftsmanship of crew members. By the time the concrete mixture is deposited ahead of the paver, there is nothing that the equipment and crew can do to improve the material properties; these properties are strictly a function of the raw materials, mixture proportions, and mixing process. *However, there are many ways that placement and finishing techniques can negatively influence what may be an otherwise acceptable concrete mixture.* From a sustainability perspective, it is imperative that the equipment and crew place and finish the concrete pavement in a manner that will maximize the performance capabilities of the concrete mixture.

The following items summarize the placing and finishing processes that are most critical to achieving the long-term pavement performance that is integral to concrete pavement sustainability. Detailed guidance regarding these practices can be found in the *Integrated Materials and Construction Practices for Concrete Pavement* (Taylor et al. 2006) and *Concrete Pavement Field Reference: Pre-Paving* (APWA 2010).

- Embedded steel must be properly placed.
    a. Dowel baskets should be placed in the proper location, anchored firmly, and positively marked to ensure that saw cuts for contraction joints are made at the proper location.
    b. Inserted dowels should be monitored for movement and positively marked to ensure that saw cuts for contraction joints are made at the proper location.
    c. Tiebars should be placed at the proper depth and spacing.
    d. Continuous reinforcing bars should be spaced according to specifications and supported in a manner that will prevent displacement during the paving process.
- Concrete should be well consolidated but not segregated. Vibrator frequency should be monitored and adjusted to variations in the concrete mixture and the paver speed. Cores of the pavement should be taken as soon as possible and visually inspected to verify that consolidation efforts are adequate and not detrimental.
- Proper hand finishing techniques should be consistently implemented.
    a. Except in rare and isolated conditions, *water should not be used as a finishing aid*. The practice of adding water to the surface of the pavement can result in a weakened layer of non-durable paste at the pavement's surface.
    b. Care must be take not to over-finish the surface. Over-finishing results in a paste-rich, high-permeability surface layer, which is susceptible to shrinkage cracking and surface scaling.
- Acceptable pavement smoothness characteristics must be achieved by following best practices for placing and finishing.

Managing Economic Impacts

- Paving equipment should be matched to project conditions.
- Subgrade and subbase(s) should be placed to thickness and smoothness tolerances that will minimize waste and meet thickness tolerance specifications for the concrete pavement.

Managing Environmental Impacts

- Smooth pavements improve fuel efficiency.
- Dust should be controlled by sprinkling with water.

Managing Societal Impacts

- Construction noise should be mitigated to reduce impacts on surrounding areas.
- Dust should be controlled by sprinkling with water.
- Smooth pavements reduce wear and tear on vehicles.

Surface Texturing

Concrete pavement surface textures provide the friction needed for safe roadways. Surface textures have also been shown to be the primary contributor to pavement-tire noise. There are three basic types of concrete pavement surface textures, as shown in Table 5.2.

Guidance regarding improved procedures for concrete texturing that contribute to constructing quieter pavements can be found in How to Reduce Tire-Pavement Noise: *Interim Better Practices for Constructing and Texturing Concrete Pavement Surfaces* (Rasmussen et al. 2008).

Managing Economic Impacts

Diamond ground textures generally cost more than tined or drag textures.

Managing Environmental Impacts

Slurry from diamond ground textures should be collected and disposed of properly.

Managing Societal Impacts

- Adequate friction characteristics must be provided for safe roadways.
- Studies have shown that tire-pavement noise is attributable to positive texture on concrete pavements. Quieter pavements have textures with fewer positive projections in the surface.

Curing Concrete

Perhaps one of the most overlooked parts of the concrete paving process, curing has a significant impact on concrete pavement durability and thus on sustainability. Curing must be executed properly to prevent excessive moisture loss and thus to ensure that sufficient water is available in the concrete to completely hydrate the cementitious materials and to prevent shrinkage cracking and excessive warping.

In general, white pigmented curing compound should be applied before any surface evaporation occurs. All exposed surfaces of the concrete pavement should be completely covered (the pavement surface should be uniformly white). Precautions should be taken to

Table 5.2 Concrete Pavement Surface Texture Types

	Texture Types		
	Tined (Figure 5.9)	**Drag** (Figure 5.10)	**Diamond Ground** (Figure 5.11)
Variations / Uses	• Transverse, uniform spacing • Transverse, random spacing • Longitudinal, uniform spacing	• Burlap • Artificial turf • Broom	• New surface • Restored surface

Figure 5.9 Longitudinal tining (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Figure 5.10 Artificial turf drag texture (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Figure 5.11 Diamond-ground texture (Rasmussen et al. 2008)

insulate the concrete during cold weather curing to prevent the pavement from freezing before gaining sufficient strength.

Managing Economic Impacts

Although curing compounds and the curing process itself constitute one of the least expensive components of the concrete paving process, premature failures associated with inadequate curing result in unnecessary future maintenance and rehabilitation expenditures.

Managing Environmental Impacts

- Some curing compounds may contain materials that could be hazardous to the environment. If spills occur, they should be contained and mitigated in accordance with local regulations.
- Use of environmentally benign curing compounds should be considered when allowed by specification.

Managing Societal Impacts

Prevention of premature pavement distresses and related repair activities through the proper application of curing compound and techniques reduces work zone-related traffic delays.

Sawing and Sealing Joints

Sawed joints are necessary for non-reinforced pavements to prevent uncontrolled cracking. Practices for sawing and sealing joints vary across the United States. The most common options for green sawing concrete pavement are wet sawing with diamond blades (saw cut depth = T/4 or T/3) and early entry sawing using a dry diamond blade (saw cut depth = 1 in. to 3 in.).

Dimension sawing (joint widening) is necessary for certain joint sealants that require a specific joint shape for proper performance. This is most commonly performed by wet sawing with stacked diamond blades that create a joint reservoir from ⅜ in. to ½ in. wide and 1 in. to 1½ in. deep.

Common joint sealant materials used for concrete paving include bituminous (hot poured or cold poured), silicone (tooled or self-leveling), and pre-formed compression seals.

Managing Economic Impacts

- The cost and performance of joint sealants varies widely. When specifying a joint sealant, performance expectations should be balanced by cost-benefit analyses.
- Some states choose to leave joints unsealed. This decision should be based on actual performance studies that are applicable to the intended climate, subbase design, and pavement use conditions.

Managing Environmental Impacts

- Slurry from wet sawing joints should not be allowed to drain unfiltered into adjacent waterways.
- Some joint sealants may contain materials that are hazardous to the environment and/or crew; manufacturers' recommendations should be followed.

Managing Societal Impacts

- Measures should be taken to prevent the dust generated by dry sawing joints from obstructing the visibility of adjacent traffic.
- Tire-pavement noise associated with wide joints (>½ in.) may be objectionable.

3. New Developments in Concrete Pavement That Could Improve Sustainability

Two Lift Concrete Pavements

As discussed in Chapter 3, two-lift paving is a technique that is commonly used in Europe. The construction process involves placing two lifts of concrete pavement, with the top lift placed on the bottom lift while it is still wet (Figures 5.12 and 5.13). Typically the bottom lift is approximately 80 percent of the thickness and the top lift is approximately 20 percent. Constructing a concrete pavement in this manner allows for the use of different mixture designs for the bottom lift and top lift.

Two-lift pavements can be constructed with conventional paving equipment, although an additional belt placer/spreader and an additional paver is required. It is possible to offset these additional labor and equipment costs by economizing the mixture design used for the lower lift.

Two-lift pavements offer opportunities to improve the sustainability of concrete pavements in the following ways:

- Utilization of recycled pavement materials in the lower lift
- Increased use of supplementary cementitious materials in the lower lift
- Long-term performance enhancements associated with an ultra-durable wearing surface

Roller-Compacted Concrete

Roller-compacted concrete (RCC) is constructed using equipment similar to that used in the asphalt pavement construction industry (Figure 5.14). The mixture is placed with a heavy-duty paver and compacted with a vibratory steel wheel and pneumatic rollers. RCC mixtures utilize a greater amount of fine aggregate particles and reduced cementitious and water contents (Harrington et al. 2010). RCC contains no reinforcing steel, reducing both the economic and environmental impacts from the use of steel reinforcement. In certain geographic areas that have an abundance of natural sands and a shortage of quality coarse aggregates, higher aggregate content makes RCC a sustainable solution for low-speed applications (industrial lots, streets, and local roads). RCC can also be opened to light traffic earlier than conventional concrete pavement, resulting in less disruption to the traveling public.

Figure 5.12 Top lift being placed on the bottom lift (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

Figure 5.13 Two-lift paving on I-70 in Kansas (photo courtesy of Gary Fick, Trinity Construction Management, Inc.)

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Figure 5.14 RCC placement (Harrington et al. 2010)

Chapter 6

IMPACT OF THE USE PHASE

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As discussed in previous chapters, to obtain a full measure of the environmental impact of a concrete pavement, all phases of the pavement's life cycle must be considered. Although considerable attention has been paid to the material acquisition and construction phases, and to a lesser degree the end-of-life phase, until recently little attention has been paid to the impact of pavement type during the use phase. Yet it is recognized that the use phase, particularly the traffic using the facility, often has the largest impact on the environment (Wathne 2010). As a result, increasing emphasis is being placed on whether differences resulting from pavement type may have a significant effect on environmental impact over the life cycle, considering such factors as vehicle fuel efficiency as well as how the pavement interacts with the environment while in service (Wathne 2010, Santero et al. 2011a).

This chapter briefly considers both aspects. Traffic-related factors such as vehicle rolling resistance, which is influenced by pavement roughness and stiffness, are discussed, as is pavement-environment interaction including carbonation, lighting requirements, albedo, and leachate. The latter are discussed in greater detail in Chapter 9, as they are primarily a consideration in urban environments.

1. Vehicle Fuel Consumption

Unlike buildings that have electricity and other energy-related metrics directly attributed to their use, the energy and associated environmental impact attributed to the use of pavements are more difficult to account. Although some of the energy used in the operation of a pavement may be directly accounted for (e.g., energy to power artificial lighting), the biggest source of energy consumed during the use phase is overwhelmingly the fuel consumption of vehicles using the roadway. The consumption of fossil fuels has the greatest environmental impact during the pavement life cycle, due in part to the emission of GHGs, but also many other environmentally harmful impacts as shown in Figure 6.1.

Vehicle fuel consumption depends on many things such as wind resistance, vehicle type and load, tire type and pressure, vehicle speed and acceleration, and the interaction between the vehicle and the pavement surface, which includes pavement roughness (often measured using the international roughness index or IRI), surface texture, and stiffness, among other factors. Many of these factors are the same regardless of pavement type. Pavement roughness, surface texture, and stiffness, however, are inherent features of the pavement and thus can be controlled by the managing agency, which has the ability to design, construct, and maintain a pavement surface that will minimize the economic and environmental impact of vehicle operation.

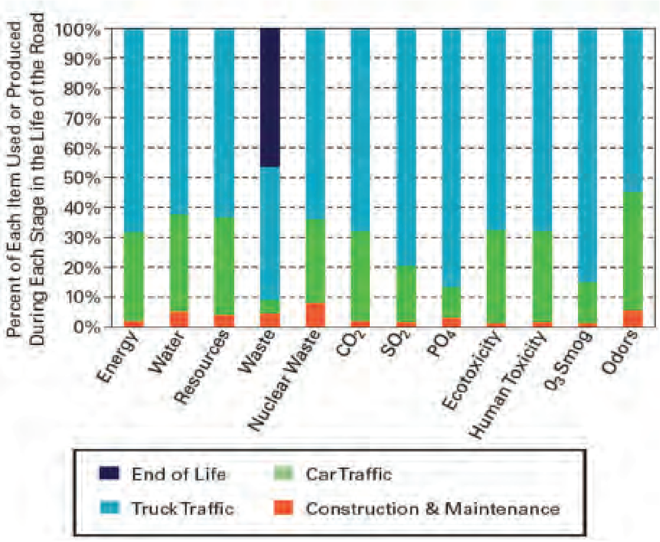

Figure 6.1 Ecoprofile of different life-cycle phases from a typical road (Wathne 2010 based on EAPA 2004)

The rolling resistance, which is the vehicle energy loss associated with pavement-vehicle interaction, has to be minimized for agencies to improve the fuel efficiency of vehicles operating on their pavements (Santero et al. 2011b). One of the biggest factors contributing to rolling resistance is road roughness, as it results in an excitation of the suspension systems in vehicles, consuming energy that is responsible for significant increases in fuel consumption (AASHTO 2009). This has been a key input into the World Bank's pavement design model for decades (Chesher and Harrison 1987, Bennett and Greenwood 2003), and recent studies have confirmed the validity of this conclusion (Zabaar 2010). Specifically, it was found that regardless of pavement or vehicle type, increasing pavement roughness results in significantly higher fuel consumption regardless of vehicle speed. This clearly demonstrates the benefit of constructing smooth pavements and keeping them smooth over their service life.

Further, increasing pavement texture (as measured by the sand patch test) results in significant increases in fuel consumption at lower vehicle speeds (Zaabar 2010). Sandberg (1990) had previously observed this trend, finding that at higher speeds, rolling resistance is less dependent on pavement surface texture because vehicle fuel consumption is more heavily influenced by air resistance.

These conclusions, which are consistent with previous work conducted on vehicle operating costs, support the need to construct smooth, safe, and quiet concrete pavements and employ maintenance and preservation strategies over the service life that will keep them smooth, safe, and quiet. This enhances fuel efficiency and reduces environmental impact; it will also reduce the social cost of pavements by reducing crashes (Tighe et al. 2000). As is described in Chapter 7, the timely application of preventive maintenance treatments, including the use of diamond surface grinding, is a key strategy to keep good pavements in good condition, enhancing sustainability over the life cycle.

In addition to pavement roughness and texture, a number of field studies have been performed to determine if rolling resistance is affected by pavement properties (Zaniewski et al. 1982, De Graaff 1999, NPC 2002, Taylor and Patten 2006, Ardekani and Sumitsawan 2010, Zaabar and Chatti 2011). Higher pavement deflections may result in additional fuel consumption as a vehicle moves along the pavement surface (Akbarian 2011).

It is clear from past studies that no overwhelming consensus has emerged from various field studies conducted to determine whether pavement type impacts fuel consumption, although it appears that pavement type can make a difference, with slightly better fuel efficiency observed for vehicles operating on concrete pavements (Santero et al. 2011c). From this review, it is clear that the study of fuel consumption is complicated by many, many factors, and those field studies that have taken this into account have found that pavement type effects are most prevalent for heavier, slow-moving vehicles during warm weather. As an example, Zaabar and Chatti (2011) reported that pavement type has a statistically significant impact on fuel efficiency for light (loaded) trucks and heavy trucks moving at low speeds (35 mph) under summer conditions, with increased fuel consumption occurring on asphalt-surfaced pavements. The results were statistically insignificant at higher speeds for all vehicles, and for passenger cars, vans, and SUVs under all conditions. It is noted that data were not available for heavy trucks under winter conditions.

These results make sense from an intuitive perspective since a viscoelastic material such as asphalt will stiffen as it cools and/or is subjected to a higher rate of loading. As the surface stiffens, deflection decreases and rolling resistance is reduced. Work conducted at the Massachusetts Institute of Technology resulted in a first-order mechanistic model to simulate the effect of pavement stiffness on rolling resistance and to accurately calculate the rate of fuel consumption for different vehicle types for pavements of various stiffness (Akbarian 2011). Preliminary results suggest that pavement stiffness does make a small but significant difference, with lower fuel consumption incurred for all vehicle types operating on stiffer pavements. The continued development of this type of model is justified, as the volume of traffic over the life of many pavements is so great that even a difference in fuel consumption of only 1 or 2 percent can have a huge economic and environmental impact over the design life and should be incorporated into a life-cycle assessment model as discussed in Chapter 8.

In summary, it is clear that vehicular operations are responsible for most of the energy consumed and emissions generated over a pavement's life cycle. Although many factors contributing to fuel consumption are not related to the interaction between the tire and pavement, the pavement roughness, texture, and stiffness contribute to the rolling resistance. A concrete pavement that is constructed and maintained in a smooth condition will thus reduce rolling resistance and increase fuel efficiency of vehicles operating on it, thus reducing energy use and emissions. Further, the inherent stiffness of concrete appears to result in reduced fuel consumption, especially for heavy vehicles operating at slow speeds during the warmer months of the year. Mechanistic models are under development that will properly consider vehicular rolling resistance and its impact on fuel consumption for use in life-cycle assessment.

2. Other Environmental Impacts During Use

In addition to environmental impact incurred due to vehicular use, other environmental factors warrant consideration, including solar reflectance, lighting, carbonation, run-off, and traffic delays. Santero et al. (2011a) note that these factors are the least consistently considered in the environmental life-cycle assessment of pavements, yet in combination they can have a significant environmental impact. Most of these factors are addressed in greater detail in other chapters, but they are mentioned here since they affect a pavement in service.

Solar Reflectance

Solar reflectance (or albedo) is a surface property of a material. Solar reflectance values range from zero to 1.0, with a zero value indicating a perfectly non-reflective material and a 1.0 value representing a material that is 100 percent reflective. Light-colored materials have higher solar reflectance values than dark-colored materials. Although color plays a role in a material's solar reflectance, color alone is not the only indicator of solar reflectance.

Solar reflectance has the greatest importance in urban areas as it is known to contribute to the formation of urban heat islands. A heat island is a local area of elevated temperature located in a region of cooler temperatures. Heat islands usually occur in urban areas as illustrated in Figure 6.2; hence, they are sometimes called urban heat islands. Urban heat islands are formed due to the warming of exposed urban surfaces such as roofs and pavements (EPA 2009). Urban heat islands contribute to lower air and water quality and greater energy demands, especially in the summer.

In places that are already burdened with high temperatures, the heat-island effect can make cities warmer, more uncomfortable, and occasionally more life-threatening (FEMA 2007). Temperatures greater than 75°F increase the probability of formation of ground-level ozone (commonly called smog), which exacerbates respiratory conditions such as asthma. Higher temperatures also lead to greater reliance on air conditioning, which leads to more energy use and associated emissions.

Due to its naturally light color, concrete is an excellent choice for paving material in an urban environment. This is illustrated in Figure 6.3, which shows the impact of pavement albedo on surface temperature, with darker surfaces having much higher temperatures. Further, reflectance can be enhanced by the use of some SCMs, such as light-colored slag cement and/or fly ash. Highly reflective pavement surfaces can be created using white titanium dioxide photocatalytic cement or coatings, further mitigating the urban heat island effect. Titanium dioxide photocatalyic coatings have the added benefit of breaking down the harmful compounds of nitrogen oxides (NOx) (Chen and Poon 2009). And, because of evaporative cooling, the use of a light-colored pervious concrete pavement can be extremely effective in addressing the urban heat island while also addressing surface run-off. Further discussion on this topic can be found in Chapter 9.

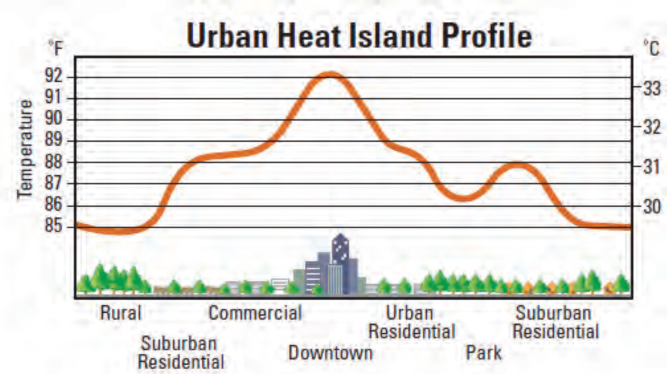

Figure 6.2 Heat islands for various areas of development (EPA 2003)

Further, the use of reflective surfaces, including the use of reflective pavements and roofs in both urban and rural areas, is being advocated by a group of researchers at Lawrence Berkeley National Laboratory. This is not being recommended for mitigation of the urban heat island effect alone, but as a strategy to combat global warming through radiative forcing of the sun's energy back into space (Akbari and Menon 2008). The basic theory is that when the sun's energy is reflected back into space, it is not being absorbed into the earth's surface and thus cannot contribute to warming of the planet. Research continues into the impact of radiative forcing on mitigating global warming, but findings to date indicate that this could be an enormously important factor in reducing global temperatures in the future.

Lighting

Concrete's higher (brighter) reflectance can also lower infrastructure and ongoing lighting costs, while boosting safety for vehicles and pedestrians. Concrete

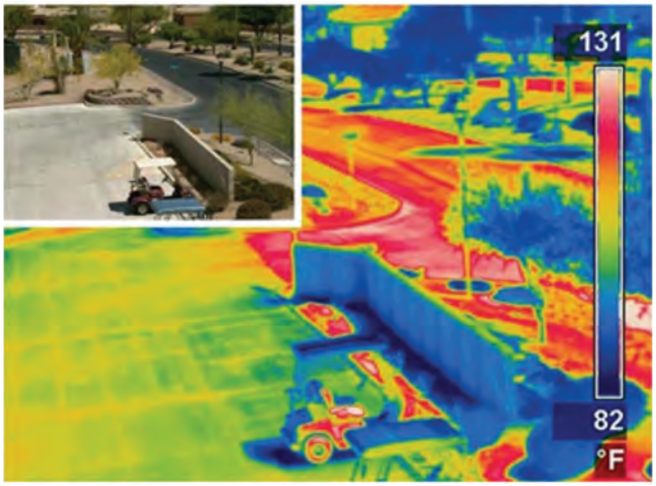

Figure 6.3 Effect of pavement type and albedo on pavement surface temperature (Kaloush 2010)

pavements require fewer lighting fixtures than other surfaces and less energy is required to achieve the same degree of lighting (Gajda and VanGeem 2001). Improved illumination leads to increased visibility, which is an important safety consideration. This is also discussed in more detail in Chapter 9.

Carbonation

Carbonation is a normal phenomenon that occurs between hydrated cement phases in concrete and atmospheric carbon dioxide (CO_2), where the phases react with the CO_2, absorbing some of it into the exposed surfaces. By reabsorbing atmospheric CO_2, concrete pavements can partially offset their environmental impact of CO_2 generation that occurs during the manufacture of cement. Gajda (2001) gathered data on the amount of CO_2 that could be absorbed by concrete based on more than 1,000 samples. Figure 6.4 shows one sample that has carbonated to a depth of 18 mm. Carbonation rates varied depending on the strength of the concrete and cement content, but the average rate of carbonation for uncoated concrete was found to be 4.23 mm/yr$^{0.5}$. He further estimated that, on average, concrete produced in the United States could absorb about 274,000 metric tons of atmospheric CO_2 in the first year after placement. Although the rate of carbonation will slow with time, it is important to know that a measurable amount of CO_2 will be sequestered by a concrete pavement while in service.

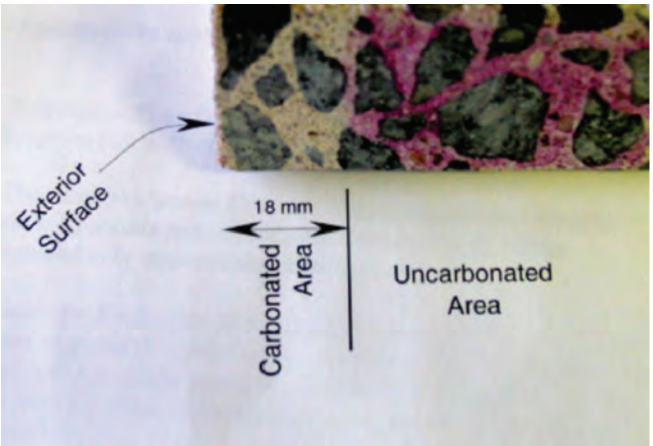

Figure 6.4 Depth of carbonation determined by the phenolphthalein test (pink two-thirds of the sample is not carbonated (Gajda 2001)

As is discussed in Chapter 8, significant additional amounts of CO_2 can be absorbed through carbonation at the end of a pavement's life, particularly if it is crushed as part of a recycling operation.

Run-Off and Leachate

After a rainstorm, run-off from the pavement surface can carry pollutants with it, most of which originated from vehicles that used the pavement and not from the pavement material itself (Santero et al. 2011b). The use of a pervious concrete surface (currently applicable for low traffic volume pavements, parking areas, and shoulders) can help mitigate some of this effect by preventing most surface run-off from directly entering streams and lakes (Borst et al. 2010). Instead, natural processes degrade the pollutants as the water slowly passes through aggregate and soil. Further, pervious concrete surfaces will prevent run-off warmed by a hot pavement surface from rapidly entering surface waters, thus helping to maintain a cool water temperature which is necessary for some species' survival. As pervious concrete is most often used in urban areas, Chapter 9 includes a more detailed discussion on this topic.

Santero et al. (2011b) also noted that research has been inconclusive related to run-off or leachates from recycled materials. It is known that when concrete is recycled and stockpiled, run-off from the stockpiles initially has a pH of 9 or 10, but the pH diminishes within weeks as exposed cement grains and soluble cement paste phases react (ACPA 2009). Additional discussion on the use of recycled concrete is presented in Chapter 8.

Traffic Delays

Traffic delays incurred during pavement maintenance and rehabilitation (see Figure 6.5) greatly influence vehicle fuel consumption. Santero et al. (2011a) hypothesize that traffic delays could be a much greater portion of a pavement's environmental impact than construction materials and equipment. As a result, it is recognized that the environmental impacts of traffic delay resulting from future maintenance and rehabilitation activities should be included in the environmental assessment, and work continues to characterize this impact (Santero et al. 2011c). The inclusion of this impact would further demonstrate the environmental savings that can be incurred through long-life pavements that have little need for future lane closure in support of maintenance/rehabilitation activities.

3. Summary

Studies have recognized the importance of considering the use phase in sustainable design, yet often it is largely ignored. Pavement designers, contractors, and owners may not have influence on the types of vehicles that use pavements. However, with proper consideration during design and construction and the adoption of an aggressive concrete preservation strategy, concrete pavements can be constructed and maintained in a smooth condition, reducing fuel consumption and related emissions. Over the life cycle, small improvements in fuel efficiency incurred due to the inherent stiffness of concrete pavements may significantly reduce the environmental impact of pavements. Further, the relatively high reflectivity of concrete will help reduce the heat island effect, reduce the energy needed for artificial illumination, and through radiative forcing reduce global warming, further enhancing environmental performance during the use phase. Other factors that should be considered include carbonation, run-off and leachate generation, and traffic delays incurred during future maintenance and rehabilitation activities. Work is under way to better characterize the environmental impacts that are incurred through the use phase and to determine how these can more easily be included in environmental life-cycle assessment. Indications are that the use phase has the greatest impact of all life-cycle phases and thus must be considered in sustainable design.

Figure 6.5 Traffic delays caused by construction (photo courtesy of Jim Cable, FHWA)

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Chapter 7

CONCRETE PAVEMENT RENEWAL

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Preservation and rehabilitation play an important role in ensuring pavement longevity while maintaining the highest level of serviceability. Long-lasting pavements reduce future investments in new materials and construction, thus minimizing economic, environmental, and social impact over the life cycle. Further, a well maintained concrete pavement will remain in a smooth, safe, and quiet condition for a greater portion of its life, thus increasing the fuel efficiency of vehicles and reducing crashes that adversely impact the community. As such, renewal directly contributes to the sustainability of the concrete pavement.

This chapter briefly discusses renewal strategies that can be applied to concrete pavements to effectively maintain serviceability over the design life. The two primary strategies that are discussed are preventive maintenance and rehabilitation. Preventive maintenance is a planned strategy employing treatments that extend pavement life, generally without increasing structural capacity. Pavement rehabilitation adds some structural capacity, usually through the application of additional pavement thickness in the form of an overlay. Timely and appropriate preventive maintenance and rehabilitation can enhance sustainability over the concrete pavement life cycle.

1. Pavement Renewal Concepts

Although many treatments and strategies are available that contribute to concrete pavement renewal, they can generally be classified under preventive maintenance or rehabilitation. Preventive maintenance is a planned strategy employing cost-effective treatments (e.g., patching, joint sealing, diamond grinding, and so on) that extend pavement life without increasing structural capacity (Smith, Hoerner, and Peshkin 2008). Unlike preventive maintenance, pavement rehabilitation adds some structural capacity, usually through the application of additional pavement thickness in the form of an overlay (Harrington et al. 2008).

Figure 7.1 graphically illustrates a typical pavement life, with pavement "condition" (e.g., level of distress, roughness, structural capacity, and so on) plotted on the vertical axis and time (or traffic) plotted on the horizontal axis. The curved line represents pavement performance over time, showing initially that pavement condition slightly decreases with time as the pavement ages and is subjected to traffic. After the initial phase of the pavement life, performance decreases at an increasing rate before finally leveling off once it has reached a poor condition.

Figure 7.1 also shows typical "windows" in which preventive maintenance and rehabilitation are applicable. As can be seen, preventive maintenance is only applicable when the pavement is in relatively good condition and has significant remaining life. Thus, a common precept is that preventive maintenance is used to keep good pavements in good condition. In some cases maintenance may be required on high traffic lanes only, in which case detailing should avoid elevation differences between lanes. Pavement rehabilitation is appropriate after the pavement condition has dropped to a point where it is no longer effective to apply preventive maintenance. As can also be seen in Figure 7.1, after the pavement condition has dropped to a certain level—the pavement life is basically "used up"—the only suitable treatment is reconstruction.

Figure 7.2 illustrates the monetary impact of treatments applied at various pavement condition levels, as represented by a generalized pavement condition rating (PCR). It shows that $1.00 spent to maintain a good pavement (PCR 60 to 100) in good condition is equivalent to spending $4.80 to $7.00 on a pavement having a PCR of 50 to 60. This cost jumps to $20.00 at a PCR of 40 to 50, and to $48.00 at a PCR less than 40, illustrating the cost effectiveness of properly applied preventive maintenance treatments.

The effects of preventive maintenance and rehabilitation are illustrated in Figure 7.3. As can be seen, each application of a preventive maintenance treatment provides a small increase in condition, often translating to increased smoothness. Thus, the application of timely and appropriate preventive maintenance treatments will keep a smooth pavement smooth for an extended period of time. This is not only cost effective for the agency responsible for maintaining the pavement but, as discussed in Chapter 6, it also reduces the vehicle operating costs as well as the environmental impact of vehicles operating on the pavement.

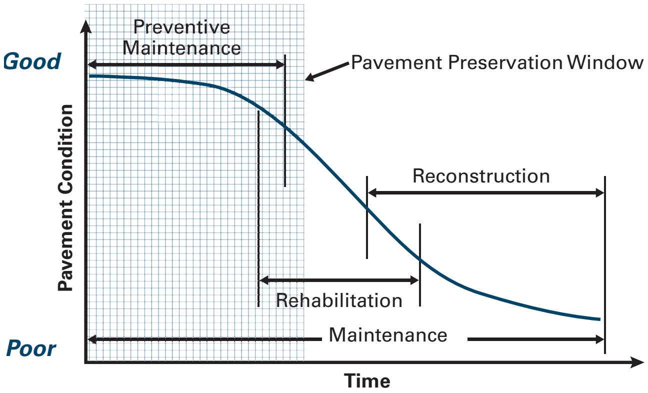

Figure 7.1 Typical pavement performance curve showing ideal times for the application of pavement preservation, rehabilitation, and reconstruction (Smith, Hoerner, and Peshkin 2008)

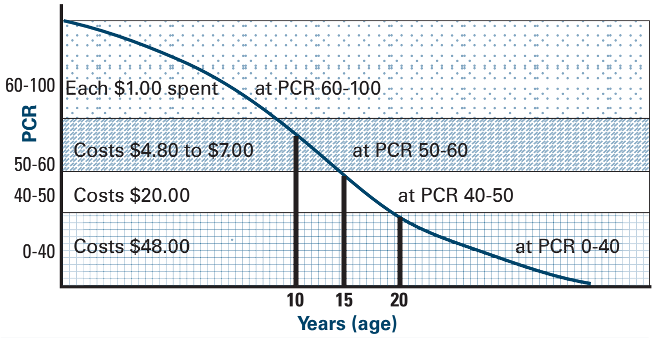

Figure 7.2 Comparison of treatment costs at different pavement condition ratings (PCRs) (Zimmerman and Wolters 2003)

At some point, preventive maintenance alone may be incapable of maintaining the pavement in a smooth condition indefinitely, and therefore the application of a rehabilitation treatment is needed to restore structural capacity. This is illustrated in Figure 7.3, where a large improvement in condition is realized through the application of the rehabilitation treatment. However, the underlying condition of the original pavement affects the life of the rehabilitation; thus, after rehabilitation, pavement condition may decrease at a faster rate than it does for a newly constructed pavement.

In summary, the concept of concrete pavement renewal requires that preventive maintenance and rehabilitation techniques be employed, using the right treatment at the right time. To be cost effective while reducing life-cycle environmental impact, preventive maintenance treatments are applied to pavements in generally good condition, keeping them smooth while extending life. Over time, the structural capacity of most pavements will need to be restored or increased, at which juncture the use of pavement rehabilitation techniques will be the best approach.

2. Pavement Evaluation Overview

Determining "the right time" and the "right strategy" (maintenance or rehabilitation) requires a thorough pavement evaluation (Smith, Hoerner, and Peshkin 2008). Not understanding the pavement condition can result in the application of an inappropriate treatment and, consequently, either an early failure or wasteful over-design. For example, a recent study of economic and environmental life-cycle performance of concrete pavements found that when the life of a rehabilitation treatment was not fully utilized, it resulted in significant environmental cost (Van Dam et al. 2011). Thus, the first step in any preventive maintenance/rehabilitation project is an evaluation of the existing conditions. A typical concrete pavement evaluation will consist of the following steps (Smith, Hoerner, and Peshkin 2008):

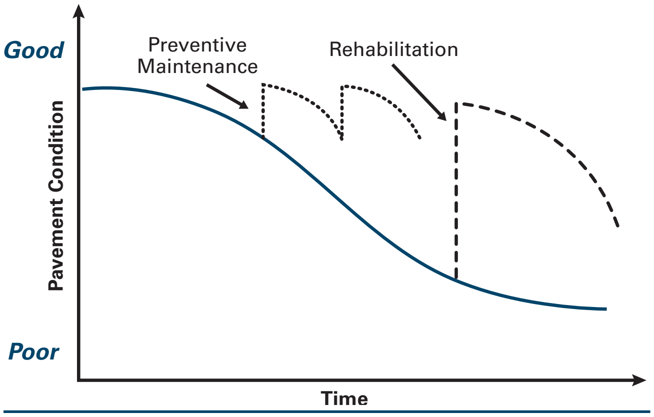

Figure 7.3 Illustration of typical impacts of preventive maintenance and rehabilitation on concrete pavement condition (Smith, Hoerner, and Peshkin 2008)

1. *Review of historical data and records* – This should include a review of design reports, construction plans and records, materials and soils properties, past performance and maintenance records, past and anticipated future traffic, and climatic conditions.

2. *Initial site visit and assessment* – This consists of an initial visit to assess general conditions and help scope the future evaluation and includes general distress observations, an assessment of roughness, particularly sags and swells, and observation of moisture problems.

3. *Field testing activities* – These may include detailed distress and drainage surveys, nondestructive deflection testing, roughness and friction testing, and field sampling and testing.

4. *Laboratory materials characterization* – This may include determining the strength and stiffness of concrete and bound layers, petrographic analysis of concrete, density, and gradation analysis. The focus is on using the data to determine the overall pavement condition, focusing on causative effects and uniformity over the project length.

Upon completion of the evaluation, a determination will be made whether the pavement is in good condition, as defined by the owner, and possesses adequate structural capacity to be suitable for preventive maintenance, or whether the conditions are such that structural improvement is required through the use of rehabilitation. It is important to note that, if the pavement is deteriorating due to a materials-related distress (MRD) mechanism, such as alkali-silica reactivity or freeze-thaw damage, it may not be a good candidate for preventive maintenance strategies that do not address the underlying distress mechanism.

The following sections will discuss preventive maintenance and rehabilitation treatments, and how their use results in increased sustainability over the life cycle.

3. Preventive Maintenance Treatments

Concrete pavement preservation treatments include the following (Smith, Hoerner, and Peshkin 2008):

- Slab stabilization
- Partial-depth repair
- Full-depth repair
- Use of precast panels in full-depth repairs
- Retrofitted edge drains
- Load transfer restoration
- Diamond grinding and grooving
- Joint resealing and crack sealing

Not all projects will include all treatments. The most common treatments that address ride quality are partial- and full-depth repairs, load transfer restoration, and diamond grinding. These are discussed below. Cross stitching may be conducted on newer pavements that have early-age cracks (ACPA 2006). When thin bonded concrete overlays are constructed primarily to restore ride quality rather than add structural capacity, they may be considered as preventive maintenance projects; overlays are described in detail under the Rehabilitation section of this chapter.

Partial-Depth Repair

Partial-depth repairs are used to repair surface distress that is isolated in the top one-third of the slab, restoring ride quality and allowing for effective sealing of joints (Frentress and Harrington 2011). This type of distress is often found in the vicinity of joints and is most often caused by the infiltration of incompressible material into the joint that results in spalling as the joint closes during warmer weather. Poor concrete consolidation, localized areas of weak concrete, corrosion of reinforcing steel, and the use of joint inserts also contribute to the formation of surface distress that can be addressed through partial-depth repairs. Traffic is often a contributing factor, as joint displacement can "pinch" the concrete at the surface and dislodge concrete weakened by other factors.

The conventional repair sequence includes the following (Smith, Hoerner, and Peshkin 2008):

1. Repair boundaries are determined, ensuring that all the deteriorated/delaminated concrete is identified for removal.
2. Concrete is removed using partial-depth saw cuts to define repair boundaries and light-weight jack hammers to carefully remove the concrete from repair area.
3. Repair area is prepared by final removal of loose material and cleaned using sand-blasting and air-blasting.
4. Joint is prepared, including insertion of a compressible material into the joint to prevent intrusion of the repair material.
5. For some repair materials, bonding grout/agent must be applied immediately prior to placement of the repair material.
6. The patch material is placed in accordance with manufacturer's instructions.
7. The patch is cured for the specified time, often using a white pigmented membrane curing compound. Blankets may be required in cooler weather.

A recent publication discusses how concrete removal can be conducted quite efficiently using modern milling machines in which rotating carbide teeth grind away the existing concrete to the desired depth, leaving a rough substrate that facilitates bonding of the repair material (Harrington et al. 2011). See Figure 7.4. This technique has been used successfully in a number of states, creating cost-effective, long-lasting repairs.

Several materials are available for partial-depth repairs, with the choice being driven by the desired time to opening. Long-lasting, durable repairs have been created using portland cement-based products, although if the required time to opening is less than 12 hours, often proprietary cementitious- or polymeric-based materials are used (Smith, Hoerner, and Peshkin 2008, Harrington et al. 2011). The selection of the repair material is based on multiple factors that are assessed as part of operations and maintenance.

Full-Depth Repair

Full-depth repairs, including full slab replacements, are used to repair various types of structural distress including transverse cracking, corner breaks, longitudinal cracking, severely deteriorated joints (distress extends deeper than one-third the slab depth), blowups, and punch-outs. These distresses compromise the structural integrity of the pavement system, and the use of full-depth repairs restores the lost capacity while improving ride quality. If the distress is present through a large percentage of the project, full-depth repairs may not be cost effective. Instead, a structural rehabilitation using an overlay might be more effective and potentially result in a more sustainable solution (Smith, Hoerner, and Peshkin 2008).

Full-depth repairs of jointed concrete pavement are accomplished according to the following steps:

1. Repair boundaries are identified, ensuring that the entire potential extent of deterioration is incorporated. Figure 7.5 illustrates that often the distress at the bottom of the slab extends beyond what is visible at the surface, and the effectiveness of the repair is dependent on the complete removal of deteriorated concrete.
2. The concrete is sawed the full depth of the slab, ensuring a smooth face for restoration of load transfer devices. Multiple saw cuts may be used to facilitate removal of the concrete.
3. Concrete is removed in a way that minimizes disruption to adjacent concrete and the underlying base. The lift-out method, in which lift pins are attached through drilled holes, has been found to be most effective, although other methods have also been successful.
4. The repair area is prepared by removal of loose material, replacing it with compacted materials of similar properties or with concrete. As compaction within the confined repair area is difficult, replacement with concrete is often the best approach.
5. Load transfer at the transverse edges of the repair is restored through the use of steel dowels, which are grouted into holes created using gang-mounted drills.
6. Concrete is placed and finished in accordance with appropriate specifications. Typically conventional concrete can be used, although often a high-early or even a very high-early strength mixture can be selected. In general, it is best to use accelerated strength gain mixtures only if the constraints of the project dictate that early opening to traffic is required, as the economic and environmental impact of the repair material can be increased if early strength gain is specified. Use of recycled materials may help to balance this negative impact.
7. Curing is typically accomplished using a white pigmented curing compound. Blankets may be required in cooler weather and/or if accelerated strength gain is desired.

Figure 7.4 Damaged material has been milled out in a partial-depth repair (photo courtesy of Dale Harrington, Snyder and Associates)

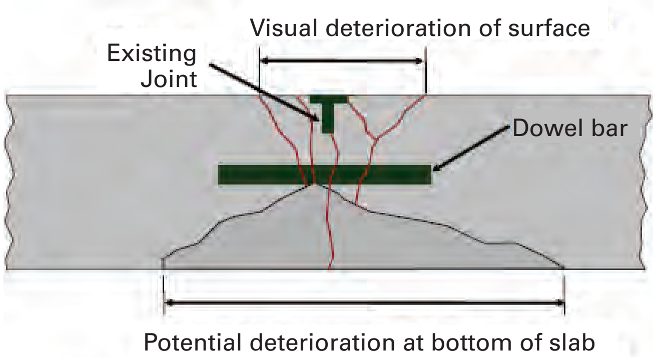

Figure 7.5 Illustration of distress extent, with distress at the bottom of the slab extending beyond that observed at the surface (Smith, Hoerner, and Peshkin 2008)

Full-depth repairs are used when deterioration extends beyond one-third the slab depth and safety and ride quality are compromised. Well constructed full-depth repairs should last for the life of the concrete pavement, effectively restoring structural integrity and ride quality, and are thus an important treatment used to maintain concrete pavements over the life cycle.

Load Transfer Restoration

The restoration of load transfer is a technology that has had a significant impact on improving the ride quality of concrete pavements throughout the United States. It was not uncommon in the past to construct jointed plain concrete pavement (JPCP) without load transfer devices, with the assumption that aggregate interlock would be sufficient to maintain load transfer with shorter joint spacing. Unfortunately, it has been found that JPCPs constructed without load transfer devices are susceptible to joint faulting, resulting in poor ride quality even though the pavement is otherwise sound. Further, in some jointed concrete pavements with load transfer devices, faulting has occurred as heavy traffic has eventually degraded the ability of the joint to transfer load. In either case, load transfer restoration has provided an avenue to restore the ability of load to be shared across a joint, minimizing deflection and reducing cracking, thus positively affecting remaining life. Once load transfer is restored, the primary mechanism causing faulting is eliminated. Assuming drainage is also addressed using edge drains, and that the slabs have been restored to desired elevations, the pavement can then be diamond ground to improve ride quality. Load transfer restoration is illustrated in Figure 7.6.

The current practice for restoring load transfer is as follows (Smith, Hoerner, and Peshkin 2008):

1. Slots for dowel bars are created using gang-mounted saw blades mounted on specially designed slot-cutting machines. Production rates exceeding 2,500 slots per day are possible using this method.
2. Each slot is prepared using a lightweight jack hammer to carefully scalp the concrete from the slot and then using a hammerhead to flatten the bottom of the slot. The slot is then cleaned by sand-blasting and air-blasting to provide a surface with which the repair material can bond. The existing joint is then caulked to prevent intrusion of repair material
3. A dowel bar is placed in each slot. The dowel bar is typically on a chair, coated with a bond breaker and capped with an expansion cap on one or both ends. A compressible insert is located at the bar center to establish the joint in the repair. Figure 7.7 shows dowel bars adjacent to prepared slots, waiting to be placed.
4. Repair material is placed in the slot according to the manufacturer's recommendations and consolidated with a small, spud-type vibrator. The repair is then finished and cured to minimize shrinkage. The repair material is critical to the success of this treatment. Most materials that are suitable for partial-depth repair are suitable for this application.

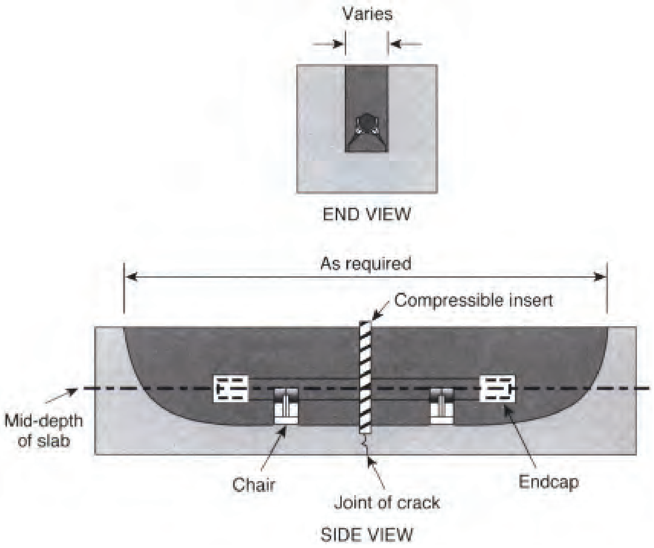

Figure 7.6 Schematic illustration of load transfer restoration (ACPA 2006)

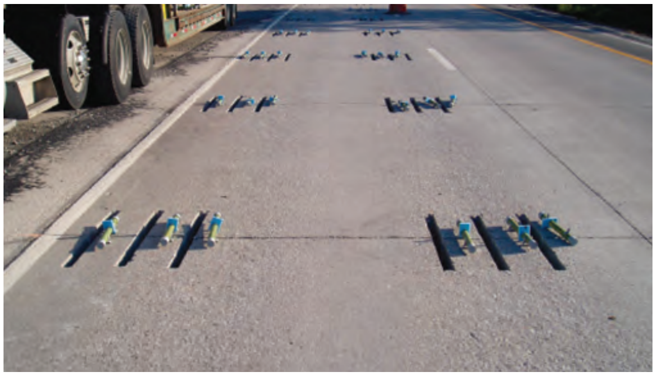

Figure 7.7 Dowel bars on chairs with end caps and compressible inserts in place ready to be inserted into prepared slots (IGGA 2010)

With the advent of slot-cutting machines, which ensure good productivity and quality, load transfer restoration has become a popular operation to address poor load transfer that is common in undoweled JPCPs and in older pavements in which load transfer has been lost. In combination with diamond grinding, load transfer restoration can be used to effectively maintain a concrete pavement in a smooth condition over its design life.

Diamond Grinding

Diamond grinding is applied to a concrete pavement after partial- and full-depth repairs and load transfer restoration, as well as slab stabilization and drainage retrofitting. Using gang-mounted, closely-spaced diamond saw blades, diamond grinding uniformly removes a thin layer of concrete, restoring pavement ride quality while improving skid resistance. This treatment removes faulting, wheel path wear, surface irregularities, and polished surface texture, replacing them with a uniform surface that can be as smooth, quiet, and safe as the originally constructed surface. Figure 7.8 shows a close-up of a diamond ground surface, showing how it is renewed without the need to add any new material.

Diamond grinding has been in use for decades, having been pioneered in California where it was first used in 1965. California continues to routinely apply this technique, finding that a ground pavement will maintain its smoothness for 16 to 17 years before the need to regrind, with some projects receiving three successive grindings over their design life in regions without studded tires or chains (Stubstad et al. 2005).

Figure 7.8 Diamond ground surface after years of service (photo courtesy of The Transtec Group)

In general, pavements with faulting in excess of 0.125 in., IRI roughness of 63 to 90 in./mi, or wheel path wear up to 0.375 in. are good candidates for diamond grinding. More specifically, the following guidelines apply (Smith, Hoerner, and Peshkin 2008):

- Exceedingly rough pavements having an IRI in excess of 190 in./mi may be too rough to be successfully ground in a cost-effective manner. In such cases, rehabilitation through the use of an overlay may be more appropriate (Correa and Wong 2001).
- Severe drainage problems must be addressed prior to diamond grinding.
- Structural distress must be repaired prior to diamond grinding.
- If load transfer efficiencies are below 60 percent, load transfer restoration must be completed prior to diamond grinding.
- The harder the aggregate, the more difficult and expensive it is to grind. In some instances, it may be cost prohibitive to effectively grind a concrete made with extremely hard aggregates.
- If there is need for significant full-depth repair and slab replacements, the structural life of the pavement may be near its end and thus diamond grinding would not be a good option.
- As with other preventive maintenance treatments, if the pavement is deteriorating due to a materials-related distress (MRD) mechanism, such as alkali-silica reactivity or freeze-thaw damage, it may not be a good candidate for diamond grinding.

As a treatment that can improve overall ride quality and skid resistance in a cost-effective manner, diamond grinding has the potential to significantly improve vehicle fuel efficiency and safety, thus contributing directly to improved sustainability. Also, there have recently been efforts to remove asphalt overlays from some concrete pavements that were overlaid primarily to address ride quality issues (IGGA ND). These pavements then undergo preventive maintenance treatments and diamond grinding, returning them into service as renewed concrete pavements. This has the advantage of minimal future maintenance costs as well as increased reflectivity, thus lowering life-cycle environmental impact.

Summary

In summary, preventive maintenance plays a critical role in keeping good pavements in good condition. Treatments such as partial- and full-depth repair replace deteriorated concrete while restoring ride quality and structural integrity of the pavement. Load transfer restoration slows the progression of future faulting and, combined with diamond grinding which eliminates existing faulting, results in the long-term restoration of ride quality. Preventive maintenance is thus a cost effective, low-environmental impact approach to reducing vehicle operating costs and associated emissions over the pavement life cycle.

4. Rehabilitation

As defined by Harrington et al. (2008), pavement rehabilitation through an overlay can be considered as minor rehabilitation or major rehabilitation, differentiated primarily by the thickness of the overlay and the degree to which structural capacity is increased. As mentioned previously, thin bonded concrete overlays are constructed primarily to restore surface quality and are generally considered to be preventive maintenance projects. Bonded concrete overlays may also be considered minor rehabilitation in that they generally add some structural capacity to pavements. Unbonded concrete overlays, which are generally 4-in. thick or more, comprise minor and major rehabilitation projects, involving structural enhancements that extend service life.

Concrete overlays can be placed on existing concrete, asphalt, and composite pavements. This chapter, however, focuses on overlays of existing concrete pavements. Various pavement conditions for which different types of concrete overlays are appropriate are illustrated in Figure 7.9.

Bonded Concrete Overlays

In certain circumstances, a bonded concrete overlay provides a good treatment option to eliminate surface defects (e.g., extensive scaling, poor aggregate friction characteristics, and so on), infill a milled section, and/or increase the structural capacity of an existing concrete pavement, while meeting vertical clearance requirements. In general, the existing concrete pavement must be in good structural condition. The keys to successful use of a bonded concrete overlay are as follow (Harrington et al. 2008):

- The existing substrate pavement surface must be thoroughly prepared and cleaned to enhance the bond between it and the overlay.
- The coefficient of thermal expansion of the overlay concrete must be similar to that in the substrate concrete.
- Working cracks in the existing pavement must be repaired, or the overlay should be sawed over them to prevent uncontrolled reflective cracking in the overlay.
- Existing joints must be in fair to good condition or repaired.
- Joint sawing must be done promptly following construction of the overlay.
- Transverse joints in the overlay must be sawed full depth plus 0.5 in., whereas longitudinal joints must be sawed to half the overlay thickness.
- Joints in the overlay must align with those in the underlying pavement.
- The width of the transverse joints in the overlay must be the same or greater than the width of the crack in the transverse joints in the underlying pavement.
- Curing compound must be applied in a timely and thorough fashion.

As the name implies, a good bond between the overlay and the existing substrate pavement must be achieved during construction and must be maintained during the life of the pavement, as the loss of bond will result in premature failure of the overlay. Thus, great care must be exercised during construction to ensure that the substrate is properly prepared, that construction is done as specified, that the joints are sawed promptly and to the correct depth, and that curing is conducted expeditiously and with care. The following is a summary of the bonded concrete overlay process (Harrington et al. 2008):

1. *Pavement evaluation* – The pavement should be thoroughly evaluated to ensure that it is a good candidate for a bonded concrete overlay. In general, it must be structurally sound, relatively free of distress, and must not be suffering from an MRD.

2. *Overlay design* – Bonded concrete overlays are typically 2- to 5-in. thick, and thickness is commonly designed using the AASHTO (1993) *Guide for Design of Pavement Structures*, although the use of the new AASHTO Darwin-ME design will continue to grow in popularity. Conventional concrete mixtures have been successful in constructing bonded concrete overlays. Joint design must match the existing concrete pavement.

3. *Pre-overlay repair* – Pre-overlay repair is essential for the successful performance of bonded concrete overlays. Table 7-1 provides recommendations regarding the type of distresses that require repair and suitable treatments. As the overlay is intimately bonded to the substrate, existing distress will have a tendency to reflect through unless addressed. After repairs are conducted, the surface should be roughened and thoroughly cleaned to enhance bonding.

4. *Construction* – Key elements of construction include concrete placement, curing, and joint sawing. Although conventional construction techniques are used, curing is especially critical because the thinness of the layer gives it a high surface area to volume ratio, making it very susceptible to moisture loss. Also, as the underlying pavement will continue to move in response to changing temperatures, it is critical that joint sawing be initiated as soon as possible to minimize the chance for random cracking.

When well designed and constructed correctly, a bonded overlay will extend the life of a concrete pavement for decades, providing a sustainable solution to correct specific problems in an existing structurally sound concrete pavement. See Figure 7.10.

Table 7.1 Pre-Overlay Repair Recommendations for Bonded Concrete Overlays (Harrington et al. 2008)

Existing Pavement Distress	Spot Repairs to Consider
Random cracks	Reflective cracking is likely if no repairs are made; use crack cages or full-depth repairs for severe cracks
Faulting	Slab stabilization
Pumping	Slab stabilization
Asphalt patch	Replace with concrete patch to ensure bonding
Joint spalling	Partial-depth repair
Scaling	Remove with cleaning

Figure 7.10 Bonded overlay

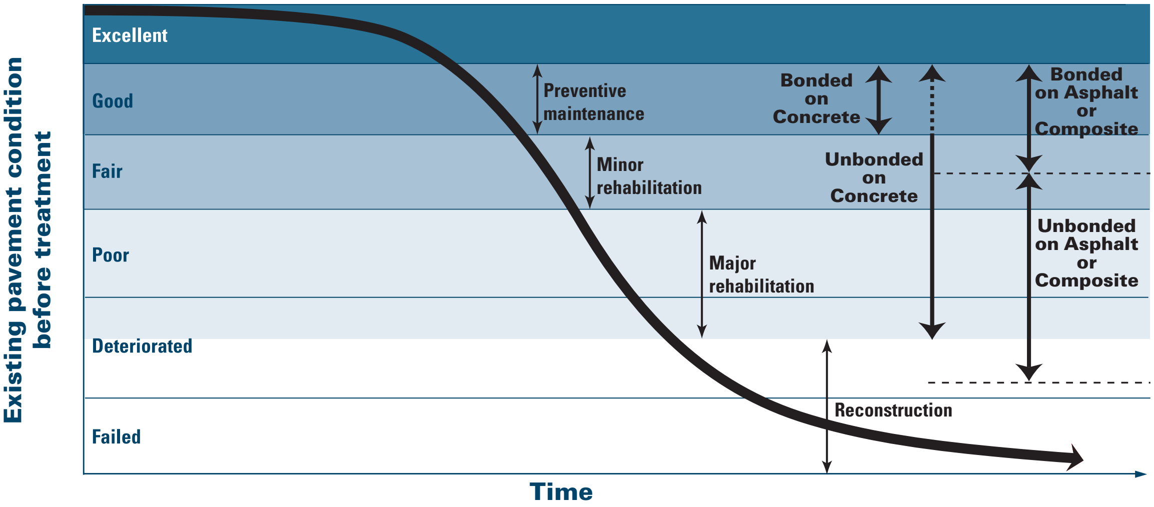

Figure 7.9 Typical applications for bonded and unbonded concrete overlays on existing concrete and asphalt/composite pavements (Harrington et al. 2008)

Unbonded Concrete Overlays

Unbonded concrete overlays have been successfully used in the rehabilitation of concrete pavements for decades and are viable treatments to address concrete pavements with some structural deterioration. Since the overlay is essentially designed as a new concrete pavement, it can restore load-carrying capacity, providing a new riding surface and extending pavement life. The overlay has an effective service life similar to a newly constructed concrete pavement.

Unbonded concrete overlays are typically 6- to 11-in. thick, depending on the anticipated traffic and the condition of the underlying pavement (Harrington et al. 2008). As the name implies, the overlay is purposely separated from the underlying slab; that is, it is designed independently, considering the existing pavement as a base. As such, unbonded concrete overlays do not require extensive pre-overlay repair, nor do joints need to be matched with those in the underlying slab. The keys to effectively using an unbonded overlay are as follow (Harrington et al. 2008):

- The existing pavement is in poor condition but is stable and uniform. Material-related distress (MRD) is not a concern as long as continued expansion will not result in blow-ups.

- Ideal applications are existing pavements that require significant improvement in structural capacity and/or serviceability (ride quality, skid resistance, and so on).

- Full-depth repairs are conducted only in isolated locations where structural integrity must be restored.

- Traditionally, the overlay is separated from the underlying pavement through the use of a thin (1-in.) asphalt layer. Recent use of a thick, nonwoven geotextile as the separation layer has been promising, and this strategy is likely to grow in acceptance (Rasmussen and Garber 2009).

- Faulting is generally not a problem if it is 0.38 in. or less and if a 1-in. thick asphalt separation layer is used.

- Joint sawing must be done promptly following construction of the overlay.

- Shorter joint spacing than normal is often needed to reduce stresses due to temperature curling.

- Joints do not need to be matched or purposely mismatched.

As the overlay is isolated from the underlying pavement, this treatment is ideal for concrete pavements that are near or at the end of their life but can still provide good, uniform support for the new overlay. The following is a summary of the unbonded concrete overlay process (Harrington et al. 2008):

1. *Pavement evaluation* – The existing pavement should be evaluated to ensure that it can provide good uniform support for the unbonded concrete overlay and, if not, to determine what actions are needed to obtain uniformity. Although a candidate pavement can be suffering MRD, the evaluation should confirm that future expansion will not result in blow-ups of the underlying pavement in time.

2. *Overlay design* – Unbonded concrete overlays are typically 6- to 11-in. thick, and thickness is commonly designed using the AASHTO (1993) *Guide for Design of Pavement Structures*, although the use of the new AASHTO mechanistic-empirical design will continue to grow in popularity. The separation layer has traditionally been a 1-in. thick hot-mix asphalt surface course, although the use of thick, nonwoven geosynthetics is showing promise. Conventional concrete mixtures have been successfully used in constructing unbonded concrete overlays. Joint design includes the use of dowel bars for unbonded overlays 8-in. thick or greater and the use of short joint spacing to minimize temperature curling stresses. Typical joint spacing is shown in Table 7-2. Drainage must be considered to avoid damage to the asphalt separation layer. Edge support should be provided with tied concrete shoulders in lieu of widened overlay slabs to avoid high curling stresses.

3. *Pre-overlay repair* – Typically only distresses resulting from major loss of structural integrity require pre-overlay repair for unbonded concrete overlays. Table 7-3 provides recommendations regarding the type of distresses that require repair and suitable treatments.

4. *Construction* – Key elements of construction include concrete placement, curing, and joint sawing. Although conventional construction techniques are used, curing is especially critical if a relatively thin unbonded overlay is used because of the high surface area to volume ratio, making it very susceptible to moisture loss. Also, it is critical that joint sawing be initiated as soon as possible to minimize the chance for random cracking, as the underlying high level of restraint and stiff support will result in rapid development of tensile stresses.

Unbonded concrete overlays continue to enjoy popularity as an excellent strategy for the rehabilitation of concrete pavements nearing the end of their useful life. See Figure 7.11. The overlay has all of the sustainability advantages inherent in a newly constructed concrete pavement, without the added economic and environmental costs associated with crushing and removing the existing pavement and transporting and compacting new base material. In effect, the agency retains and builds on the equity invested in the original pavement. The amount of fuel used to construct an overlay is reportedly considerably less than that used for new construction, thereby reducing the impact of the rehabilitation. Further, traffic delays during construction are minimized, as the existing pavement provides an excellent working platform, minimizing delays due to weather that can be problematic when removing the existing pavement and constructing the base. Finally, since unbonded concrete overlays are typically thinner than a newly constructed pavement designed for the same traffic loading, unbonded overlays provide additional economic and environmental benefits through the use of less material. In combination, these factors make unbonded overlays a very sustainable treatment option to rehabilitate pavements nearing the end of their useful life.

5. Summary

The application of proper concrete pavement preventive maintenance and rehabilitation strategies is essential to extend the life of a concrete pavement while ensuring that it remains in a structurally sound, smooth, and safe condition over its life cycle. Applying the right strategy at the right time contributes to the overall sustainability of the pavement by ensuring it meets or exceeds its

Table 7.2 Recommended Transverse Joint Spacing for Unbonded Concrete Overlay (Harrington et al. 2008)

Unbonded Resurfacing Thickness	Maximum Transverse Joint Spacing
< 5 in. (125 mm)	6 x 6 ft (1.8 x 1.8 m) panels
5–7 in. (125–175 mm)	Spacing in feet = 2 times thickness in inches
> 7 in. (175 mm)	15 ft (4.6 m)

Table 7.3 Pre-Overlay Repair Recommendations for Unbonded Concrete Overlays (Harrington et al. 2008)

Existing Pavement Condition	Possible Repairs to Consider
Faulting 0.25–0.38 in. (6–10 mm)	None
Faulting > 0.38 in. (10 mm)	Thicker separation layer
Significant tenting	Full-depth repair
Badly shattered slabs	Full-depth repair
Significant pumping	Full-depth spot repair and drainage improvements
Severe joint spalling	Clean
CRCP with punchouts or other severe damage	Full-depth repair

Figure 7.11 Unbonded overlay

design life with minimum impact. Not only are economic savings maximized, but the negative economic and environmental impacts of vehicle operations are minimized as well, while the pavement is maintained in a safe condition. The techniques described in this chapter offer a variety of preventive maintenance tools to address deterioration that results from usage and time. In particular, the use of load transfer restoration and diamond grinding has been shown to extend the life of a concrete pavement in a very cost-effective and environmentally friendly manner. As a concrete pavement nears the end of its useful life, it can be rehabilitated through the use of an unbonded overlay, essentially constructing a new concrete pavement on the surface of the old pavement. Thus, an engineer skilled in the use of these and other strategies in the pavement preventive maintenance and rehabilitation toolkit can sustainably manage concrete pavements into perpetuity.

6. References

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Chapter 8

END OF LIFE RECYCLING CONCEPTS AND STRATEGIES

David Gress

The ultimate goal of recycling is to achieve a zero waste stream target utilizing all byproduct materials encountered in the rehabilitation or reconstruction of a concrete pavement. Not only is this economically advantageous but in addition local recycling minimizes environmental impact by reducing the carbon footprint, embodied energy, and emissions and enhances social good by reducing the need for landfills and the extraction of nonrenewable raw materials. Achieving this goal ensures that a balance is struck among the economic, environmental, and social factors that are considered in the construction of concrete pavements. As discussed in Chapter 2, the concept of recycling must be viewed as a cradle-to-cradle undertaking as opposed to past thinking of cradle to grave. There is no practical grave for materials used in modern sustainable infrastructure, only a new beginning which allows application of current technologies to achieve the goal of zero waste in the rehabilitation and reconstruction of concrete pavements.

Driven by cost, need, limited resources, and an environmental awareness of the benefits of sustainability, concrete pavement recycling technology continues to advance. In the past, economic cost was the driving force that encouraged recycling, yet this is beginning to change. Although cost will remain an important driver, the social and political awareness of the need to be sustainable has recently become more significant. This is especially true in regions of high population density where limited availability of construction materials very often leads to cost-effective options for recycling concrete pavements into new recycled concrete and unbound base material. In addition, land-use sensitivities, traffic considerations, as well as overall cost are also of greater importance in urban areas. The benefits of recycling include the following:

- Economic savings
- Reduced use of limited nonrenewable raw materials
- Decreased demand for fuel and associated emissions from transport of waste to landfill and of new materials to the site
- Improved land use, by minimizing both the need for landfills and the need to develop more land for resource extraction

1. Introduction to Recycled Concrete

A subtle but important benefit of recycling concrete is the potential benefit of reducing atmospheric carbon dioxide (CO_2) through carbon sequestration. The paste of the original concrete has approximately 25 percent free calcium hydroxide (CH) which is potentially capable of sequestering a significant amount of the carbon dioxide that was initially released during cement manufacturing due to the calcination of the limestone (calcium carbonate). Sequestration is simply the process of reversing the calcination that occurred in the kiln when atmospheric CO_2 reacts with CH present in the hardened concrete to form calcium carbonate ($CaCO_3$). The rate of sequestration varies directly with temperature, surface area, relative humidity, and concentration of CO_2. Work through the Recycled Materials Resource Center (RMRC) at the University of New Hampshire has shown the potential benefit of sequestering carbon dioxide using the free CH found in recycled concrete aggregate (RCA).

Sequestering is more efficient when RCA is used as base material due to favorable environmental conditions in a pavement subsurface base system as compared to concrete exposed during normal service which carbonates slowly due to minimum exposed surface area, low moisture contents, and low matrix permeability (Gardner 2007). When concrete is crushed the resulting RCA has increased surface area exposing more CH to the atmosphere which accelerates the rate of carbonation (Haselbach and Ma 2008).

Even though concrete recycling is a proven technology, it is not uncommon for the public as well as some governmental agencies to discredit its benefits due to a perception that the concrete is a waste material and therefore of little use. Overcoming this requires a positive attitude among the various stakeholders including the responsible transportation agency, the environmental agency in control, contractors, producers, and the public. Success requires a common understanding that recycled concrete is not a waste product and that concrete has added value after it has been removed and processed. To be successfully utilized, recycled concrete must be viewed as another source of aggregate with characteristics and value equivalent to the aggregate material it replaces ton for ton.

Additional information on the use of recycled concrete in transportation infrastructure can be found in the following resources:

- FHWA (1997)
- FHWA (2007)
- AASHTO M 319, *Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course*
- AASHTO MP 16, *Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete*
- ACPA Engineering Bulletin 043P, *Recycling Concrete Pavements*

2. RCA Properties

It is important for users to understand the physical, chemical, and mechanistic properties of RCA in relation to its proposed uses. In general, hydraulic cement concrete can easily be processed into RCA, which has added value as an aggregate replacement in new concrete, as a dense graded base material, as drainable base material, or as fine aggregate; see Figure 8.1. These RCA materials are recognized by ASTM and AASHTO as viable aggregates, and there is no need to request or apply for exceptions to standard specifications when they are utilized as new aggregate substitutes. Generally speaking, normal test criteria and specifications that apply for conventional aggregate also apply for RCA materials.

Figure 8.1 Recycled concrete aggregate (RCA) (photo courtesy of Jim Grove, FHWA)

Thorough discussions of the typical properties of RCA are found elsewhere (FHWA 2007, ACPA 2009, Obla et al. 2007).

Physical Properties

RCA is an engineered processed material that has properties dependent on its proposed use. For instance, if its proposed use is an aggregate in concrete then RCA must be processed to a higher standard than if it were to be used as unbound, stabilized or drainable base.

RCA is processed to meet the same application criteria as required of any new aggregate. Although RCA must pass the same testing requirements, it has unique characteristics which vary from conventional aggregate. For instance RCA consists of a combination of original aggregate and old mortar and is very angular with superior properties when used as a base material. The quality of RCA concrete depends on the amount of mortar that remains attached to the original aggregate. If processing is such that little mortar remains and no fines smaller than #4 sieve are used, the properties of the RCA will be similar to the properties of the original aggregate. On the other hand, if significant mortar remains and excessive fines are used, the properties of the RCA will significantly impact those of the new concrete, compromising its performance compared to concrete made with the original aggregates. This uniqueness must be accounted for so that the RCA can be used to its best value application. Essentially any grading can be achieved by varying processing procedures such as type of crusher.

The added quality value of RCA varies depending on the application requirements of its use:

- RCA concrete: highest added value
- Drainable base: high added value
- Unbound base: intermediate added value
- Stabilized base: lowest added value

One of the major differences between RCA and conventional aggregate is the absorption capacity due to the presence of the mortar fraction on the recycled particles. Absorption increases inversely with particle size, and thus substitution of fine aggregate with RCA at a rate in excess of 30 percent can result in decreased concrete strength and the development of undesirable finishing issues.

Although normally not problematic, the abrasion resistance of RCA, as determined by the Los Angeles Abrasion (LAB) test, is often reduced due to the presence of the mortar fraction. The presence of materials-related distress in concrete that is to be recycled, such as ASR and D-cracking, has no effect on the RCA unless it is to be used as aggregate in new concrete. The potential for future D-cracking in the new concrete can be mitigated by reducing the maximum size of the RCA to ¾ in. or less. Similarly, ASR can be mitigated by using normal mitigating techniques commonly used for conventional concrete (AASHTO 2010, Gress et al. 2003 and 2005).

The mortar fraction of the RCA contains CH as a byproduct of portland cement hydration which when in the presence of water goes into solution. This solution can react with atmospheric CO_2 and form a solid material called tufa which in the presence of fines can reduce the flow in improperly designed drainage systems using RCA. Conditions which lead to this are easily prevented in drainable bases (Wade et al. 1995).

Chemical Properties

The paste component of mortar adhering to the RCA particles significantly influences the overall alkalinity of RCA. The CH of a typical paving concrete is on the order of about three percent by mass of the original concrete. Calcium hydroxide in a saturated solution (1.8 grams per liter at room temperature) creates a basic pH of 12.4. Although this is a low solubility, the CH is mobile through the pore system in the mortar paste. Water draining through base material is thus expected to have a basic pH above neutral caused directly by the CH going into solution. A drainage base effluent, except for unusually slow or stagnant flow or the very first flushing of RCA with a high fines content, will never be supersaturated, so the pH will be significantly less than 12.4. Regardless, once the effluent exits the drainage system, the pH will quickly be reduced towards neutral by either dilution with water or neutralization with soils and organics.

RCA produced from concrete located in the northern tier of the United States may contain high levels of chloride from the use of deicers which could cause corrosion of steel reinforcement when used in CRCP and JRCP applications. This can be mitigated through the use of noncorrosive steel, steel with a corrosion resistant coating, and/or corrosion inhibitors, and by washing the RCA prior to use in concrete.

RCA that is obtained from a concrete source that has been affected by ASR must be evaluated for remaining expansion potential if it is to be used as an aggregate substitute in new concrete and proper mitigation strategies employed if expansion potential still exists. ASR is not an issue if the RCA is to be used in unbound layers including drainable base, dense-graded bases, subbase, or fill material (Saeed et al. 2006).

Mechanical Properties

The mechanical properties of RCA are a function of the quality and size of the particles. This is the direct result of the effect of the mortar fraction which is inversely related to the fineness. Generally the coarse fractions have the least mortar so the properties of particles larger than a #4 sieve (4.75 mm) have properties similar to the original aggregate whereas the fines have inferior properties compared to the original fine aggregate. Generally RCA can be processed to have more than adequate values of abrasion resistance, soundness, and bearing strength.

3. RCA used in Concrete

State agencies have utilized RCA as aggregate in concrete pavements with well documented field performance, and surveys have been completed on the original RCA concrete pavements to validate their performances (Wade et al. 1995, Gress et al. 2009). The results of these field investigations indicate that it is possible to produce pavements from recycled hydraulic cement concrete that are equivalent in all aspects to pavements made with conventional aggregates. These pavements were shown to be performing just as well as their controls after 18 to 26 years of traffic (Gress et al. 2009). However, a survey conducted by the FHWA in 2004 when several states were visited to discuss their current recycling procedures confirmed that 100 percent of the concrete pavements that were being replaced were recycled into unbound base and drainage material rather than RCA concrete.

Properties of Plastic RCA Concrete

The higher porosity and rough surface texture of RCA has an effect on the plastic properties of new concrete. The extent of the effect is a function of the mortar fraction adhering to the RCA particles as well as the angularity of the particles. Generally, as the amount of mortar increases the effect on workability and finishability can become problematic. Limiting the amount of fines, which contain most of the old paste fraction, to 25 percent minimizes water demand increase (slump constant) by approximately 15 percent (Buck 1973, Mukai et al. 1973). The effect of harshness is easily controlled at the maximum level of substitution (30 percent) with the use of supplementary cementitious materials (SCMs) and water-reducing admixtures.

When used in concrete RCA has the tendency to absorb water and reduce slump as discussed above. The impact of this is easily controlled by applying the same fundamental pre-batching procedures successfully used with lightweight concrete. This is recommended instead of adding additional water during mixing.

Entrained air is not affected by RCA; however, the ability to entrap high amounts of air due to the angularity and rough surface area of the RCA makes it necessary to increase the total amount of air by approximately one percent to assure a good air-void system is developed (Vandenbossche and Snyder 1993).

The measurement of air content with a normal pressure meter is problematic unless it is specially calibrated for the RCA being used due to the compressible air in the voids within the old paste fraction of the mortar (Fick 2008). Use of a volumetric method of determining air content (Roll-a-Meter or air-void analyzer) avoids the potential issues of measuring air within the RCA in plastic concrete.

Properties of Hardened RCA Concrete

The physical properties of RCA can be engineered to achieve properties in new concrete similar to, or even better than, the original concrete. This is accomplished by taking into consideration the properties of the original mortar, the original aggregate, RCA grading, substitution amount, and use of SCMs and admixtures. Concrete containing RCA is easily engineered to satisfy the design of any pavement by applying basic concrete technology to specify a given mix design.

- *Strength* – The strength of RCA concrete can be easily engineered to be less than, equivalent to, or even superior to the original concrete made with natural aggregates. The primary influence is the amount of RCA fines (material passing the #4 sieve) that are used in the mix design. Strength generally decreases with increased fines; however, each mix is unique with respect to the optimum amount of fines. In general, if the substitution of RCA fines is restricted to less than approximately 25 percent, the strength of the RCA concrete will be similar to that of new concrete made with natural aggregate. Higher substitution of RCA lowers the strength. When admixtures and SCMs are not utilized to enhance RCA concrete, strength can be reduced as much as 24 percent when only coarse RCA is used and as much as 40 percent when both coarse and high amounts of RCA fines are utilized (Hansen 1986). These reductions have been shown to be the direct result of the mortar content of the RCA (Snyder 1994).

- *Modulus of elasticity* – Like strength, the static modulus of elasticity of RCA concrete is also inversely related to the RCA mortar content and the mix design of the new concrete. When admixtures are not utilized to enhance the new concrete, the elastic modulus can be reduced as much as 30 percent when only coarse RCA is used, and up to 40 percent when both coarse and high amounts of RCA fines are utilized (ACI 1994).

- *Relative density* – The relative density of RCA concrete is up to 15 percent lower due to the lighter weight mortar fraction than concrete manufactured using natural aggregate (Hansen 1986). An advantage of reduced relative density is the inflated volume relative to the weight of the RCA concrete allowing more concrete to be produced than removed from a given recycling project.

- *Volumetric stability* – The wetting and drying shrinkage of RCA concrete is also directly affected by the mortar content. Aggregates with lower elastic moduli experience higher wetting and drying strain due to significantly less restraint when the new and old paste wets and dries. Concrete can be expected to have 20 to 50 percent higher wetting and drying shrinkage when it contains coarse RCA and natural sand, and 70 to 100 higher shrinkage when it contains both coarse and fine RCA (ACI 1994). Higher moisture sensitivity requires more detailed consideration of joint design in JPCP than would be necessary in normal concrete.

  The coefficient of thermal expansion of concrete made with RCA is approximately 10 percent higher than the original concrete made from any specific aggregate, but in some cases may be as much as 30 percent higher. And, as with wetting and drying, temperature induced strains merit more detail in establishing joint spacing to alleviate potential warping and curling stresses in pavements.

  Creep of RCA concrete, typically 30 to 60 percent higher than concrete containing natural aggregates, is also increased due to higher paste content. Designing for the effect of creep is similar to what is done with lightweight aggregate concrete (ACI 1994).

- *Permeability* – The permeability of concrete made with RCA is highly affected by the water-to-cementitious material (w/cm) ratios of both the original and new concrete. The old paste adhered to the RCA particles creates a short circuit for movement of water through RCA concrete if the new w/cm ratio is less than the original. The ability of water to be transported through RCA concrete can be engineered to be less than, equal to, or greater than the original concrete by varying the w/cm ratio of the concrete containing RCA, resulting in permeability ranging from less than to more than 500 percent greater than the original concrete.

- *Durability* – The durability of RCA concrete is not significantly different from that of the source concrete. Freezing and thawing resistance, for instance, is not an issue with RCA concrete providing the new paste contains an adequate air-void size distribution. The issue is more in evaluating the air content as discussed in the plastic concrete section. D-cracking, a special case of freeze-thaw distress, has been shown to be improved when the maximum size of the RCA particles is restricted to less than the critical size to cause D-cracking (Sturtevant 2007, Gress et al. 2009).

- *Alkali-silica reactivity* – Concrete containing RCA may have potential for ASR if the source concrete contained alkali-reactive aggregate. It cannot be assumed that ASR will not develop in the new concrete if special control measures are not taken. If the RCA contains reactive aggregate, mitigation strategies must be developed, even if expansive ASR did not develop in the original concrete. Petrographic examination and remaining ASR potential expansion tests are recommended to make this judgment (Stark 1996, Gress et al. 2000a and b, FWHA 2009).

  Severely ASR-damaged concrete has been successfully recycled into new concrete with little evidence of recurrent ASR damage (Gress et al. 2009). If SCM is used as a means to mitigate ASR in RCA concrete, the appropriate dosage levels should be determined by using ASTM C 1567. Other mitigating techniques include admixtures such as lithium nitrate and low alkali cement.

- *Carbonation and corrosion* – Research indicates that rates of carbonation of concrete containing RCA is up to 65 percent higher than that of concrete containing only natural aggregate (Gardner 2007). From a sustainability view, reducing atmospheric CO_2 through carbonation is very beneficial; however, for reinforced structures, increased carbonation can cause more rapid corrosion of embedded steel reinforcing if the carbonation front reaches the depth of the steel, particularly in locations where chloride concentrations are high. These rates and depths of carbonation significantly decrease with reduced w/cm ratios (Rasheeduzzafar and Khan 1984).

4. RCA in Foundations

RCA has several applications as support material.

RCA as Unbound Base Material

Recycling concrete pavements into RCA is a viable alternative for unbound base course construction. RCA as a rule is considered a superior material for unbound applications such as bases when compared to conventional new aggregate; however, RCA may have higher value for use in other sustainable applications such as replacing natural aggregate in new concrete.

From an environmental perspective, the use of RCA as unbound base material has very significant benefits including lowering CO_2 emissions, reducing transportation fuel consumption, lessening the use of higher valued natural aggregate, and sequestering of CO_2 through carbonation of the CH within the increased surface area of the RCA particles.

While it is estimated that 100 percent of replaced concrete pavements are recycled, approximately 70 percent of all state agencies utilize RCA as unbound base course (RMRC Survey 2011). RCA has similar or better properties than natural aggregate that are essential for high-quality base course construction. For instance RCA has rougher surface texture, higher shear strength, higher rutting resistance, and higher resilient modulus. These exceptional qualities allow for unrestricted use of RCA as base materials up to and including 100 percent substitution of new aggregate. Environmental evaluation is not necessary when RCA is used for base, subbase, and subgrade improvement.

Pavements with a materials-related distress such as ASR, D-cracking, or freeze-thaw distress can be effectively used as unbound base material without concern of reduced performance. The only exception, although rare, is that in areas where an external source of sulfate is present, RCA should be utilized with great caution (Saeed et al. 2006). In such areas where exposure to sulfate is possible from subgrade soils, ground water, or other external sources, the existing concrete must be extensively evaluated for expansion resulting from ettringite formation.

It is generally accepted that after unbound RCA base is compacted, its strength and stiffness increase. A misinterpretation of this phenomenon is that this is due to hydration of unhydrated portland cement contained within the paste portion of the RCA. Instead, the increased stiffness is credited to the carbonation of very soluble CH released by the RCA in the presence of moisture, which is constantly available in the subsurface base.

Testing criteria for RCA are similar to those required for natural aggregate; typically, this is a non-issue for RCA derived from concrete utilized in pavements. One exception is the sulfate soundness test (ASTM C 88) which destroys the RCA paste fraction due to sulfate attack. This test should not be specified for evaluating RCA as it has no relevance to the performance of RCA as an unbound base material. It is also sometimes difficult to pass the aggressiveness of the LAB hardness test if the concrete was made with marginal aggregate and/or when the RCA paste content is high. To address these two exceptions in RCA specifications, it is common to eliminate the sulfate soundness testing and increase the LAB limit to 50 percent.

The number-one benefit of using RCA as base material is the economic savings resulting from lower transportation costs, elimination of landfill charges to dispose of the removed concrete, and the savings derived from not buying natural aggregate base material. The use of RCA varies state by state but is typically a contractor decision in that it is not usually specified except as an option. More moisture is required during construction, but compaction is easier to obtain than with natural aggregate. As with all aggregates, control of grading and segregation needs to be given proper attention during base construction.

It is also possible to effectively utilize the existing pavement as base by employing fractured-slab techniques, thus leaving the concrete in place. Several fractured-slab techniques can be used including rubblization and crack and seat. As these two techniques are done in place, no trucking, crushing, or aggregate grading is required and thus costs are lowered. Newer in-situ recycling techniques have been deployed on a number of projects that actually go a step further than fractured-slab techniques by actually lifting the concrete off grade, crushing it, and placing it back on grade ready for compaction. The mobile crushers are track mounted, and the entire operation moves along the alignment requiring no additional trucking. Some of these in-situ recycling methods even size the aggregate to further improve performance.

To achieve a more conventional unbound base, it is necessary for the concrete pavement to be fractured, removed from the site, and crushed using conventional crushing equipment. The crusher is often sited near the pavement to reduce transportation costs and impacts. The equipment can be simple or sophisticated. The crushed material is processed and transported to its designated location for spreading and compaction. In a properly tuned crusher it is possible to return 100 percent of the crushed material as unbound base. Adding additional lanes during reconstruction easily consumes the inflated volume of base material produced, whereas if there are elevation control issues and no new lanes then it may be difficult to use 100 percent of the RCA on site.

RCA as Drainable Base

When RCA is used as a drainable base, special consideration must be given to the design. A proper design places all RCA below the elevation of the inlet of the drainage system and, if geotextiles are used, the flow must be parallel to the geotextile and not through it. Improper design will result in the formation of tufa from the fines and CH, clogging pipes and other elements of the drainage system.

Effluent from drainable bases containing RCA can have pH values greater than 7.0 due to the leaching of CH. This has not been found to be problematic in ecosystems. Although effluent from an RCA drainable base can have increased pH, especially during the first flushing cycle of water, it has no buffering capacity and is equivalent to adding lime to stabilize the effect of acid rain on a lawn. As such, there is little to no environmental impact. The ability of the CH to be removed from the paste in the leachate is a function of paste permeability which is extremely low, being on the order of 10^{-7} cm/sec. Nevertheless it must be expected that CH will slowly go into solution and be removed with flowing effluent. In stagnant flow conditions, the leachate could reach a pH as high as 12.4; however, this will quickly dissipate as the leachate encounters soils and organic materials commonly present in soils. In such cases, vegetation in the immediate vicinity of drainage structures can be affected before neutralization occurs.

RCA as Stabilized Base

RCA is easily stabilized as a base material by adding cementitious binders (such as lime and fly ash (LFATB) or portland cement (CTB)) or an asphaltic binder (ATB). As was discussed for unbound bases, the high angularity and rough surface texture of RCA makes it an exceptional base material that in many ways is superior to naturally available materials. When the cementitious content is increased, a stronger material called lean concrete base (LCB) is easily produced. The use of RCA for these applications has added value because 100 percent of the product can be utilized and there is no need to remove the fine portion of the RCA which, as discussed, is problematic for other applications. Using RCA fines in stabilized base applications has no negative impact on its physical or chemical properties.

It is also possible to use RCA to create asphalt stabilized bases (ATB). Conceptually the process is equivalent to making CTB except the effect of absorption can be problematic, not from a moisture control issue but as an economic issue since there will be an increased demand for asphaltic binder due to the absorption of the RCA. The extra absorbed asphalt binder is, for all practical purposes, unavailable for improving the base's physical properties.

5. Recycled Concrete in Other Applications

Special applications of recycled concrete are limited only by the imagination of the designer. For instance, architectural use of large irregular fractured slabs can result in the innovative use of recycled concrete ranging in size from riprap to massive slabs. Likewise, use of reclaimed rubble can be used as fill material, backfill for retaining walls, pipe bedding, artificial reefs for fish habitats, construction site soil stabilization, etc. (Vandenbossche and Snyder 1993, CMRA 2011).

- *RAP in concrete* – Concrete can be made using recycled asphalt pavement (RAP) as a portion of the aggregate, using conventional concrete mixing and construction practices. Concrete made with RAP exhibits a systematic reduction in compression and tension strengths and an increase in toughness. Generally, strength declines and toughness increases with increased amounts of RAP. The coarse particles have the least effect on these properties, suggesting that coarse RAP may be more practical to use as an aggregate substitute (Huang et al. 2005).

- *RCA in two-lift construction* – As discussed in Chapter 3, two-lift concrete pavement design is re-establishing itself in the United States and has the potential of becoming the sustainable pavement of the future. Two-lift pavement construction can be used to satisfy the economic, environmental, and social aspects essential for sustainable design. Economically the benefits include reduced capital investment and greatly increased service life with lower maintenance and rehabilitation costs. Environmental benefits include a smaller carbon footprint, reduced expended energy, and less overall pollution and waste. Societal aspects include reduced disruption, noise reduction, and improved safety through increased skid resistance.

  The future of two-lift construction for sustainable construction of concrete pavements is exceptional. It is known that the cost and availability of superior quality materials will continue to decline. The use of RCA of any quality is more than adequate for the construction of the thick underling bottom lift of the two-lift system, including RCA mixed with RAP. This reduces demand for the higher quality, costly aggregate materials typically used in the high-performance top lift. The result is a high performance pavement, consisting of a thin wear-resistant surface bonded to a tough, low-modulus, high fatigue-resistant, thick bottom lift, creating a sustainable composite pavement. Even when the pavement nears the end of its useful service life, the high quality thin top layer can easily be selectively reclaimed for reuse, thus ending the cycle of "cradle to grave" and starting the new wave of the future, "cradle to cradle"—a truly sustainable concept we can live with.

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Chapter 9

CONCRETE PAVEMENTS IN THE URBAN ENVIRONMENT

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According to the 2010 U.S. census, 83.7 percent of the 308.7 million inhabitants of the United States reside in metropolitan areas, living in core urban areas with a population of 50,000 or more (Mackun and Wilson 2011). The number of people living in urban and suburban areas is increasing while fewer are in rural areas, resulting in increased population density. Increasing density has both beneficial and detrimental effects with respect to the transportation industry. High population density means that distances traveled within the city are low (reduction in average trip distance), thus reducing fuel consumption, but it also means that considerable resources must be transported into the city, with the associated traffic and emission impacts. Cities are often surrounded by suburban sprawl, which has a highly adverse impact due to large commuting distances that are economically, socially, and environmentally costly, especially when traffic is delayed due to road maintenance. The infrastructure needs of a city are significant, including pavements, sidewalks, water, sewer utilities, and power transmission lines. Such systems are extremely sensitive to disruption, resulting in large social impacts when natural or manmade disasters occur.

Pavements represent a key element in this infrastructure, and it is estimated that paved surfaces for travel and parking can account for 29 to 39 percent of the land surface area in urban regions (Akbari et al. 1999, Rose et al. 2003). The importance of incorporating sustainability measures into the pavement life cycle is thus amplified, as environmental and societal impacts of the built environment are concentrated in urban environments. Traffic congestion and user delays, smog, safety concerns, and even aesthetics play a greater role in design because any impact has the ability to affect a larger population. Thus, potential strategies that may be cost prohibitive in a rural location may now become cost effective. Also, strategies that would not have been considered before are now applicable when the societal impacts are considered.

Concrete pavements provide unique characteristics that make them useful in an urban environment. Of specific interest in the urban environment is their longevity, which reduces interruptions (and the associated traffic impacts) for rehabilitation. Also of interest is the high surface reflectivity index (SRI) as discussed in Chapter 6. High SRI can help mitigate the urban heat island effect while also decreasing the need for and cost of artificial lighting (Marceau and VanGeem 2007). In addition, the use of photocatalytic cements and coatings can be applied in the urban environment to provide additional reflectivity while also converting NO_x, SO_x, and volatile organic compounds into solids that precipitate out and can be washed off the pavement.

Concrete can also be colored and molded to create aesthetically pleasing pavement landscaping designs that can be constructed at crosswalks or busy intersections to help slow the flow of traffic in urban neighborhoods, making them more pedestrian friendly. Additionally, concrete pavements can be effectively textured to help reduce pavement-tire noise that could otherwise detract from an otherwise quiet neighborhood. Finally, pervious concrete can be constructed in urban settings to help address critical surface storm water run-off issues.

1. The Urban Environment

A sustainable-growth strategy is to build in already densely populated areas with the goal of improving or rehabilitating existing dense zones. Undeveloped land is becoming scarce, and consumption of land for pavements, bridges, and buildings reduces the amount of land that would be otherwise available for agriculture, wildlife habitats, and parks. With any development, it is critical to implement sustainable site-development strategies by minimizing disturbance to existing ecosystems, restoring areas damaged during construction, and designing pavements, bridges, drainage systems and buildings to minimize their environmental impact. As structures are rehabilitated in urban centers, there is opportunity to add resources such as bike paths and walkways, further increasing livability and potentially reducing traffic.

Compared to rural areas, urban areas are more suitable for walking and pedestrian traffic as businesses (employers) and services (such as basic utilities, schools, banks, and hospitals) are in place (Loehr 2009) and distances traveled are much shorter. Further, larger metropolitan areas typically have alternative forms of transportation available, such as commuter trains, trams, light rail, and public buses that reduce the demand for automobile travel.

All of these attributes make cities desirable places to live, as well as more sustainable. But it also makes cities more sensitive to changes in the environment. For instance, even small disruptions to traffic flow due to construction affect many more people than in rural areas. Thus, pavement design strategies to extend design life and reduce the need for closures are extremely important in the urban environment.

2. Reducing Environmental Impacts in the Urban Environment

Concrete pavements can be part of the solution in mitigating the environmental impacts of dense urban environments.

Light, Reflective Surfaces

Concrete pavements can help reduce the urban heat island effect and the reliance on artificial lighting.

Urban Heat Island Effect

The heat island effect occurs where a local area of elevated temperature is located within a region of relatively cooler temperatures, as discussed in Chapter 6. Because of the greater density of paved and covered surfaces in urban environments, the heat island effect occurs most frequently in urban areas. The effects of urban heat islands are broad, resulting not only in increased levels of discomfort and increased energy to artificially manage temperature within buildings but also, occasionally, in life-threatening conditions (FEMA 2007). These life-threatening conditions can develop when temperatures rise above 75°F, which increases the probability of formation of ground-level ozone (commonly called smog) that exacerbates respiratory conditions such as asthma. At the same time, higher temperatures also lead to greater reliance on air conditioning, which leads to more energy use.

Mitigating the urban heat island effect is a priority for groups such as the U.S. Environmental Protection Agency (EPA), which suggests using reflective paving materials, such as conventional concrete, as one mitigation strategy (EPA 2009). Additives that can further increase the SRI of concrete, such as slag cement or light-colored fly ash, are also recommended (Van Dam and Taylor 2009).

Artificial Lighting

There are additional benefits in using light-colored concrete pavements. As Wathne (2011) discusses, light-colored pavements can also improve safety by improving night visibility while reducing artificial lighting requirements, thus saving energy and reducing emissions. Gajda and Van Geem (2001) showed that concrete pavements require fewer lights per length of roadway than dark-colored pavements to achieve the same illumination level.

In a similar study, Adrian and Jabanputra (2005) researched the influence of pavement reflectance on lighting requirements for parking lots. In their study, they compared asphalt and concrete surfaced roadways in four ways:

- Total light reflected from a surface
- Relationship of surface reflection characteristics and power distribution of lighting lamps
- Luminance and visibility levels with typical parking lot lighting systems

- Equivalent luminance of two systems based on varying lamp wattage and number of fixtures

Results of their research show that, on average, a lighter surface is 1.77 times more luminous than a darker surface and has a more uniform luminance distribution.

An analysis was also performed to create equivalent luminance levels for the two systems based on varying the number and intensity of the luminaires being used to establish the relative energy use of the two systems. When varying the lamp power and assuming that the parking lot lights are on for five hours a day, the darker parking lot used 60 percent more energy than the lighter parking lot. With modifications to the number of poles needed and still assuming that the parking lot lights are on for five hours a day, the darker parking lot used 57 percent more energy than the lighter parking lot.

In urban environments, photocatalytic cements and/or coatings may be a viable option to help maintain highly reflective surfaces. Although photocatalysts, such as the anatase form of titanium dioxide, have been known for decades to have the ability to keep surfaces clean, they have recently been gaining attention for urban infrastructure applications by incorporating it in cement (Italcementi 2005). The use of a photocatalytic titanium dioxide cement for the Gateway concrete sculptures placed at either end of the reconstructed I-35W bridge in Minneapolis in 2008 (ACI 2009) was one early U.S. application of this technology, but since then it has been used in interlocking concrete pavers (Schaffer 2009) and in two-lift concrete pavement construction (Gates 2011). A white photocatalytic material such as titanium dioxide is not only highly reflective at the time of construction, it is self-cleaning and maintains its high solar reflectance and greater visibility for a longer time. On the other hand, the material is more expensive than normal portland cement, requiring a balance between increased costs and reduced environmental impact.

Reduced Emissions, Enhanced Fuel Efficiency

As discussed in Chapter 4, one way to reduce the embodied emissions in concrete pavements is to use high supplementary cementitious material (SCM)-content binder systems and/or those containing portland-limestone cements. One such system was used in elements of the I-35W Bridge reconstruction project in Minneapolis, in which the binder for the concrete bridge piers contained 15 percent portland cement, 18 percent fly ash, and 67 percent slag cement (ACI 2009). This high-SCM-content concrete reduced the carbon footprint and embodied energy of the concrete by approximately 75 percent (Van Dam and Taylor 2009).

As discussed in Chapter 6, the energy consumed during pavement use through vehicle-pavement interaction may have a significant impact on the life-cycle energy use of the pavement. This has greater relevancy in urban areas where greater traffic volume dictates that even a minor reduction in fuel consumption and corresponding reduction in emissions for a given pavement will result in an improvement in sustainability.

In addition, vehicle emissions can also be "treated" as they interact with photocatalytic surfaces while exposed to sunlight. This has been demonstrated through laboratory experiments and in-service structures and pavements that have been constructed and monitored to determine the applicability of photocatalytic cements and coatings as a way to reduce air pollution, including NO_x, SO_x, and VOCs (TX Active® 2011). Although this technology is just catching on in the United States, concrete pavers surfaced with photocatalytic titanium dioxide are being marketed in urban areas throughout the country and the world. Figure 9.1 shows an example from Japan where photocatalytic concrete pavers have been used to create an aesthetically pleasing sidewalk while also reducing air pollution. As the effectiveness of photocatalytic cements and coatings continues to be demonstrated, their use is expected to grow in the urban environment.

Figure 9.1 Photocatalytically active colored concrete pavers in Japan (Chusid 2005)

Reduced Waste

There are only a finite number of areas available for landfilling of waste, and these areas are becoming increasingly scarce in densely populated urban areas. Typically, urban areas must dispose of waste at a landfill outside of the city or metropolitan area limits. As an example, New York City (NYC) transported over 3,000,000 tons of municipal solid waste in 2004 over great distances to other states such as Pennsylvania, Virginia, and Ohio (Lauber et al. 2006). This not only incurs a high economic cost but also generates significant environmental costs due to increased energy usage and emissions.

One way of reducing the amount of waste is to make use of the existing pavement materials. For example, innovative in-situ recycling techniques—such as recycling trains that can recycle existing pavements in place—have recently been employed on existing concrete pavements (Van Dam and Taylor 2009). These techniques reduce costs and the environmental impacts of transportation by reducing the amount of solid waste that must be transported either to crushing plants or landfills while reducing the amount of virgin materials needed on site (see Chapter 8).

Reduced Storm Water Run-off

Precipitation runs off hard, impermeable surfaces (such as pavements) much faster than off undeveloped or vegetated surfaces. The concern from the standpoint of environmental impact is that storm water systems will be overfilled when large areas of vegetation are replaced with paved or hard surfaces, resulting not only in flooding but also in erosion and the transport of pollution into nearby surface waters and increased temperatures in the streams. Typical storm water management techniques, such as retention ponds, are expensive and difficult to implement in urban areas due to lack of available land. Thus, innovative solutions are acutely needed for these locations.

One innovative solution to address the storm water quantity and quality control issue is the use of pervious concrete (NRMCA 2009); see Figure 9.2. Pervious concrete is manufactured in place with a substantial void content—between 15 percent and 25 percent—created by the use of little or no sand (Tennis et al. 2004).

With its high void content, pervious concrete allows rainwater to drain through it at a rate of about 3 to 8 gallons of water per minute per square foot of surface, as illustrated in Figure 9.3. This allows rainwater to seep into the ground versus running off, thereby recharging groundwater instead of rapidly moving from the pavement surface to nearby bodies of water. Surface water with organic contaminants is also allowed to percolate into the ground where it is filtered by the underlying soil. Thus, previous concrete can be used in urban areas to eliminate the need for other storm water management devices such as retention ponds and swales (PCA 2011).

It is important to recognize that—although the U.S. EPA (2011) cites the use of pervious concrete as a Best Management Practice (BMP) for the management of storm water runoff on a regional and local basis—pervious concrete is not applicable in all situations. For example, pervious concrete is best used in low-volume traffic applications such as roadway

Figure 9.2 Pervious concrete (photo courtesy of John Kevern, University of Missouri-Kansas City)

Figure 9.3 Water passing through pervious concrete (NRMCA 2009)

shoulders, parking lots, or alleys. It is ideal for application in urban areas where parking and alleys are a common feature.

The Chicago Department of Transportation (CDOT) has an effective program in which it is using pervious concrete in many of the city's alleys. Called the Green Alley program, one of the initiatives is to use more permeable pavements to divert storm water from the sewer system. The city is thus saved significant expense by not having to pump and treat storm water that is co-mingled with sewage. Pervious concrete pavements have been used in both center-trench and full-width applications. CDOT (2010) launched the Green Alley program because it could reap three sustainability benefits simultaneously:

- Management of storm water
- Heat-island reduction because pervious surfaces are cooler
- Use of recycled materials in the mixture

Ultimately, by integrating paving and drainage, less site area is typically needed to manage storm water, allowing a more compact site development footprint. This is critical in an urban environment.

3. Reducing Societal Impacts in the Urban Environment

Concrete's versatility makes it a good solution to create highly functional, economical pavements that also meet environmental and social needs (Van Dam and Taylor 2009). By using concrete, pavement designers can enhance communities, incorporating color and texture into aesthetically pleasing patterns, demarcating pedestrian crossings, quieting road noise, providing safer surfaces, and reducing user delays.

Enhanced Aesthetics

Concrete is an extremely moldable material and can be transformed to fit into its surroundings. Aesthetic interest can be added to concrete elements with the use of texture, color, or patterns. Although it is not likely to be cost effective for the main riding surface of a concrete pavement, cross walks, walk ways, shoulders, and other elements of the pavement can receive different treatments to add visual interest or to demarcate one area of use from another (separating vehicle and pedestrian areas, for example). At the same time, various texturing patterns can be achieved by brushing and washing away surface mortar as the concrete begins to harden, exposing the stone or gravel in the concrete, or by embedding attractive stones such as marble, granite chips, or pebbles into the surface.

Semi-hardened concrete can be pattern-stamped with special tools to create the custom look and feel of slate, cobblestone, brick, or tile. Figure 9.4 is a photograph of a Blome Granitoid pavement constructed in 1906 in Calumet, Michigan, in which the aesthetically-pleasing brick pattern was also functional, preventing horses from slipping. The patterns can help scale down large expanses of paving, as shown in Figure 9.5.

Or, simply, concrete can be cast in a wide variety of colors. Pastels and earth tones are produced by mixing mineral pigments throughout the concrete. For deeper

Figure 9.4 Blome Granitoid concrete pavement constructed in 1906 in Calumet, Michigan; the brick pattern was stamped into the surface to keep horses from slipping (photo courtesy of Tom Van Dam, CTLGroup

Figure 9.5 Modern Blome Granitoid concrete pavement (photo courtesy of Tom Van Dam, CTLGroup)

tones, finishers use the dry-shake method—sprinkling powdered, prepackaged color hardeners onto a freshly cast concrete slab, then troweling it into the surface.

Aesthetically pleasing, durable pavements can be achieved by using interlocking concrete pavers. These can also be designed to be permeable, highly reflective, and/or photocatalytic to meet a number of sustainability goals. Interlocking pavements are ideal in locations where there are underground services because if repairs are needed in the utilities, the pavers can be lifted and replaced with minimal impact.

Noise Mitigation

Noise from pavement construction or maintenance, or noise generated through tire-pavement interaction, should be considered in the quest for more sustainable pavements, as it is known that elevated noise levels can cause physiological and psychological impairments in living creatures (Hogan 2010, Passchier-Vermeer and Passchier 2000).

In urban environments, sound barriers are built to protect surrounding communities from noise generated by traffic, particularly on fast-moving expressways. Yet, through care at the pavement design stage, the need for such barriers may be eliminated if an effective noise-mitigation solution, such as use of quieter pavement surface textures, is employed.

Surface texture is desirable to increase friction and enhance safety, yet it has been shown to have a significant impact on noise generation through tire-pavement interaction (Rasmussen et al. 2007). The relationship between noise and community disturbance adjacent to roadways is not new, and pavement engineers have invested considerable effort to lessen noise generated from the interaction of the tire with the pavement surface.

Rasmussen et al. (2008) conducted research to identify factors contributing to the objectionable noise and developed pavement-noise mitigation strategies that result in safe and quiet concrete riding surfaces. Specifications have been developed (Rasmussen et al. 2011) to reduce tire-pavement noise, including the use of drag-textured or longitudinally tined surfaces (Figure 9.6) and diamond grinding including the Next Generation Concrete Surface.

However, 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. At slower speeds (less than 35 mph) engine noise is dominant; therefore, pavement texturing will have little effect on noise. In such locations, noise may less critical than aesthetics, pedestrian safety, 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 (Van Dam and Taylor 2009).

Health and Safety

The first concern of any transportation agency is to provide roadways that are safe for the user and the community. This means that, among many other factors, the surface must provide adequate surface friction while minimizing splash and spray, must not exhibit potentially hazardous distresses (potholes, faulting, blowups), and must provide enhanced night-time and poor-weather visibility for the safety of drivers and pedestrians (Van Dam and Taylor 2009).

As mentioned in Chapter 6, urban heat islands contribute to lower quality local air and water quality, which can be mitigated by the use of pavements with greater solar reflectance, such as concrete.

Reduced User Delays

There is a reason that most major metropolitan radio programs provide a traffic report every morning. Traffic and delays due to traffic are huge financial, environmental, and social issues in urban environments. Time wasted due to congestion during maintenance and reconstruction activities increases the stress of drivers, potentially negatively impacting their health. Moreover, traffic delays lead to an increase in user costs.

Figure 9.6 A potentially quiet surface (viewed from the side)

Not only do traffic delays annoy users and contribute to an increase in their costs and travel times, there is a broader environmental impact as well. The surrounding community and other populations are also affected by delays, as idling vehicles consume fuel and generate pollutants. Therefore, great benefit is derived from concrete pavement systems that minimize delay over the life cycle.

This can be accomplished through careful design (Chapter 3) and construction (Chapter 5) that minimize delay during the construction phase. This might include consideration of precast concrete pavements or other rapid construction methods. Maintaining good pavements in good condition using maintenance strategies that have minimal impact on operations is another strategy to minimize traffic delays (Chapter 7). This can be effectively achieved by performing periodic diamond grinding operations on the pavement structure, which maintains high levels of smoothness while incurring reduced environmental costs and decreased user costs. As a concrete pavement approaches the end of its structural life, concrete overlays can be rapidly constructed to restore structural capacity with far less traffic disruption than reconstruction.

4. Summary

Concrete pavements are uniquely suited to enhance sustainability in the urban environment. They are naturally light in color, which helps mitigate the urban heat island effect, increases night-time visibility for enhanced safety, and allows the reduction of artificial lighting while maintaining the same ambient light levels. Moreover, concrete pavements can be colored and textured to provide a quiet and safe surface under vehicle operations or, for slower speed applications, can be constructed to slow traffic through busy pedestrian areas by channelizing. Pervious concrete pavements are commonly used to address storm water runoff in the urban environment, whereas the use of photocatalytic materials holds the promise of treating certain air pollutants. Long-life concrete pavements also reduce the costs of traffic delays over their life cycle by being easily maintained in a smooth condition using techniques that have minimal impact on traffic operations. In combination, the properties inherent in concrete make it an ideal, sustainable choice for constructing pavements in an urban environment.

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Chapter 10

ASSESSMENT OF PAVEMENT SUSTAINABILITY

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It is well known that if progress toward a goal is not measured, the goal is not likely to be met. It is essential that the sustainable features of pavements be assessed and quantified to recognize improvements and guide innovation.

Previous chapters outlined the details about what sustainability is and how concrete pavements can be designed and constructed more sustainably. This chapter explains how the sustainability of concrete pavement can be assessed and what tools are available to assist during the assessment process. It reviews current approaches to assessing pavement sustainability, including the emerging rating systems. It presents the life-cycle assessment (LCA) approach as the path to more fully quantify the environmental and social factors contributing to the sustainability of pavements, and discusses other, emerging approaches as well. These tools should be used primarily to help guide users; they should not be used for material selection.

This is an area of fast-paced innovation, with new and updated tools constantly emerging. Some of the tools reviewed are still undergoing development and are thus likely to change in the coming year. As such, readers are encouraged to obtain the most recent information regarding the tools discussed before employing them.

1. Why Assessments are Important

Many product and service manufacturers make claims about the sustainability or "greenness" of their products and processes. It can be difficult for an owner, agency, consultant, contractor, or specifier to sort through these claims without an accurate, repeatable, and objective system to assist them in their selection.

As with any engineering challenge, such as balancing the three tenets of sustainability, tools are available to assist. In order to make the most-informed design decisions with regard to sustainability, one must employ a tool or tools that allow comparison of different design choices. The tools presented in this chapter vary in terms of complexity and level of detail, and it is important to understand the strengths and weaknesses of each in order to make the best design decision for a given project. The intent of presenting the different environmental-impact tools is to advance the state of the practice.

2. Economic and Environmental Analyses

No one tool is currently available that simultaneously considers economic, environmental, and equity (societal) impacts. Economic impacts are often assessed separately through life-cycle cost analysis (LCCA). Environmental impacts can be examined through a life-cycle assessment (LCA).

Economic Analysis

An LCCA is a powerful economic decision support tool used in the pavement type and material selection process. In an LCCA, the expenditures incurred over the lifetime of a particular pavement are accounted for. Costs at any given time are discounted to a fixed date, based on assumed rates of inflation and the time-value of money, using a discount rate. The most common discount rate used in recent years is 4 percent, but persuasive arguments are being made that this rate should be lower, based on the fact that transportation agencies do not have the option of investing money that is not spent and that the level of future funding is uncertain. Regardless of the discount rate that is used, a sensitivity analysis should be conducted using a range of discount rates to determine how sensitive the outcome is to the choice of this value.

An LCCA is performed in units of dollars and is equal to the construction cost plus the present value of future maintenance, repair, rehabilitation, and replacement costs over the life of the pavement. Using this widely accepted method, it is possible to compare the economics of different pavement alternatives that may have different cash flow factors but that provide a similar level of service.

Quite often, pavement designs with the lowest first costs for new construction will require higher costs during the pavement's life. So, even with their lesser first cost, these pavements will possibly have a greater life-cycle cost. Conversely, pavements built to last using enhanced structure and very durable materials often have a greater first cost but a lower life-cycle cost. Transportation agencies are familiar with the benefits of a lower life-cycle cost, and each state highway agency is required to do some type of LCCA when using federal funds to support large rehabilitation or reconstruction projects. Volatility in the cost of oil will affect the competitiveness of concrete on a first-cost basis (MIT 2011).

The life-cycle cost software available from the FHWA (RealCost 2011) provides economic analysis of agency and user costs during a pavement's service life. Examples of agency costs include initial engineering, contract administration, and construction costs; maintenance, repair, rehabilitation, and administrative costs; and end-of-life costs such as salvage, residual, or remaining-service-life value. User costs include vehicle operation (normal versus work-zone) costs, delay costs, and crash costs (FHWA 1998).

An LCCA is relevant only if equivalent pavement structures are being compared (for example, the same service life and design load). National standards are available for pavements to ensure design equivalency. In addition, the design life of the pavement alternatives should be stated and applied consistently during an LCCA. Analysis periods typically range around 40 years.

There is a relationship between LCCA and environmental impacts in that some environmental benefits can be converted to a monetary value. For example, lower energy use can result in lesser operating costs.

Environmental Assessment

One of the best ways to assess the environmental (and to some extent the societal) impacts of a product or process is to use life-cycle assessment (LCA). Unlike LCCA, LCA does not account for environmental impact in monetary units but instead in terms of mass or energy flows in and out of a set boundary. Whereas LCCA accrues financial impacts in terms of dollars, LCA determines environmental impacts in terms of energy or mass use (including waste and emissions generated).

An LCA is an environmental assessment of a product over its life cycle. An LCA examines all aspects of a product's life cycle—from the first stages of acquiring (whether harvested or extracted) raw materials from nature to transporting and ultimately processing these raw materials into a product (such as a pavement), using the product, and ultimately recycling it or disposing of it back into nature. Conducting an LCA of a concrete pavement is necessary to evaluate the environmental impact of the pavement over its entire life. As will be discussed, "green" rating systems and programs that focus only on a single criterion—such as recycled content or CO_2—or phase of the pavement's life—such as construction—provide only a partial snapshot of the pavement's environmental impact.

By definition, an LCA of a pavement includes environmental effects due to the following factors:

- Extraction of materials and fuel used for energy
- Manufacture of components
- Transportation of materials and components
- Assembly and construction
- Operation, including maintenance, repair, and user impacts such as energy for lighting and traffic emissions
- Demolition, disposal, recycling, and reuse of the pavement at the end of its functional or useful life

A full set of impacts—including energy use, land use, resource use, climate change, health effects, acidification, toxicity, and more—should be evaluated as part of the LCA.

An LCA involves a time-consuming manipulation of large quantities of data. A model such as SimaPro (Pré 2011) provides data for common materials and options for selecting LCA impacts. The Portland Cement Association publishes reports with life-cycle data on cement and concrete (Marceau et al. 2006, 2008).

Several organizations have proposed how an LCA should be conducted. Organizations such as the International Organization for Standardization (ISO), the Society of Environmental Toxicology and Chemistry (SETAC), and the U.S. Environmental Protection Agency (EPA) have documented standard procedures for conducting an LCA. These procedures are generally consistent with each other and are all scientific, transparent, and repeatable. As defined by ISO 14044, the four primary steps in an LCA are (ISO 2006) the following:

- Goal and scope definition
- Life-cycle inventory (LCI) analysis
- Life-cycle impact assessment (LCIA)
- Interpretation and conclusions

Definitions related to energy, and reporting of energy use in LCA, are controversial and thus are typically reported in terms of primary energy and feedstock energy. A definition of feedstock energy is "heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value" (ISO 2006). Primary energy is "energy embodied in natural resources prior to undergoing any human-made conversions or transformations" (Kydes and Cleveland 2007).

Goal and Scope—Setting the Boundary

The usefulness of an LCA or LCI depends on where the boundaries of a product are drawn. A common approach is to consider all the environmental flows from cradle to grave. It is during this phase that cut-off criteria are established for input and output to the boundary that will be quantified in the LCI stage. LCA standards recommend establishing cut-off criteria for mass, energy, and environmental significance. If the results of any two LCA analyses are to be compared, it is critical that the boundaries are the same.

During the goal and scope phase, the impact categories to be assessed are determined, as are the types and sources of data that will be collected. LCA standards also outline data quality requirements, and how to determine whether an independent, third-party review is required.

Life-Cycle Inventory (LCI)

An LCI is the second stage of an LCA. An LCI accounts for and quantifies all the individual environmental flows to and from a product throughout its life cycle. It consists of the materials and energy needed to make and use a product and the emissions to air, land, and water associated with making and using that product as illustrated in Figure 10.1.

An upstream profile can be thought of as a separate LCI that is itself an ingredient to a product. For example, the upstream profile of cement is essentially an LCI of cement, which can be imported into an LCI of concrete. To get the most useful information out of an LCI, a material should be considered in the context of its end use. The LCI of concrete itself can then be imported into an LCI of a product, such as a pavement.

The LCI of materials generally does not consider embodied energy and emissions associated with construction of manufacturing plant equipment and buildings, nor the heating and cooling of such buildings. This is generally acceptable if their materials, embodied energy, and associated emissions account for less than 1 to 5 percent of those in the process being studied. For example, LCA guidelines indicate that inputs to a process do not need to be included in an LCI if they are a small percentage of the total mass of the processed materials or product (typically less than 1 to 5 percent); they do not contribute significantly to a toxic emission; and they do not have a significant associated energy consumption. An LCI does not include labor.

Life-Cycle Impact Analysis (LCIA)

Mass and energy flowing through the system boundary are assigned to different impact categories during the LCIA phase. Impact categories can be classified as endpoints or midpoints. There is debate over where some impact categories fall. LCA practitioners generally agree on the correlation of LCI data and midpoint impact categories; endpoint categories typically require that more assumptions be made between data collected during the LCI phase and the final damage to the ecosystem.

SETAC published a document in 1999 that attempted to clarify impact categories and impact indicators. It listed midpoints such as climate change, ecotoxicity, eutrophication, and land use. Some of the endpoints listed were loss of resources, damage to humans, and damage to wildlife and plants.

Though endpoints may be less accurate, some are still important to monitor during an LCA. According to ASHRAE 189.1, results of an LCA should include the following impact indicators (ASHRAE 2009):

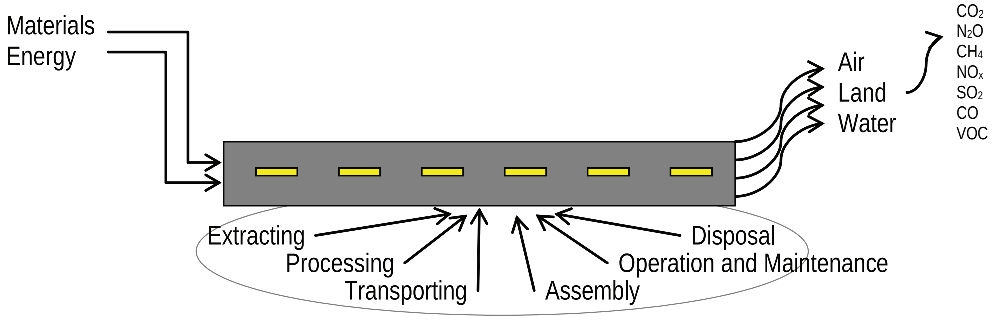

Figure 10.1 An LCI accounts for all materials and energy needed to make and use a product, and the emissions to air, land, and water associated with making and using that product

- Acidification
- Climate change
- Ecotoxicity
- Eutrophication
- Human-health effects
- Land use (or habitat alteration)
- Ozone layer depletion
- Resource use
- Smog

Weighting can be conducted during this stage of an LCA, but it is generally preferred to list results by impact category. According to ISO 14044, weighting "shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public" (ISO 2006).

Interpretation

Conclusions of the LCA are presented and analyzed during the interpretation and conclusion phase. During this portion of the LCA, the practitioner identifies any significant issues from the LCI and LCIA phase. Finally, completeness, sensitivity, and consistency checks are performed to evaluate the quality of the analysis.

LCA Case Study

Although more owners and product manufacturers are undertaking LCA to make design decisions, few reports are available to the public. Reasons for this lack of available data include concerns about disclosure of proprietary information and unfavorable interpretation of results by competitors and decision makers. In the following case study, a full range of impact categories is evaluated. Other studies, such as that conducted by the Athena Sustainable Materials Institute (Athena 2006), considered only two impact categories.

It is strongly recommended that LCA practitioners evaluate, at a minimum, a range of endpoint impact categories including acidification, climate change, ecotoxicity, eutrophication, human-health effects, land use (or habitat alteration), ozone layer depletion, resource use, and smog creation. It is noted that the accuracy of some of the models used to predict the endpoint impact categories listed previously are often not as accurate as those used to predict the midpoint indicators such as energy use or CO_2 equivalents. Performing an LCA without considering these endpoint impact indicators does not assess the full environmental impact of a product, design, or system. Nonetheless, the following case study illustrates how a limited LCA evaluation can be used to significantly reduce the environmental impacts of a given pavement type through improved design and materials choices.

The Kansas Two-Lift Concrete Pavement Demonstration Project was constructed on I-70 near Salina, Kansas, in 2008 (National Concrete Pavement Technology Center 2008). The Right Environment of Austin, Texas, conducted an LCA to compare a traditionally constructed pavement section (Alternative No. 1) to the as-built two-lift pavement (Alternative No. 2). A third alternative, an optimized two-lift design using higher levels of recycled and industrial byproduct material (RIBM), was also considered in the LCA. The basic sections evaluated are illustrated in Figure 10.2, and the mixture designs are presented in Table 10.1.

It is clear that Alternative No. 2, which is the as-built two-lift pavement section, had a number of innovative features beyond the use of the two-lift design. The 40-mm top-lift surface concrete used a wear-resistant imported rhyolite coarse aggregate, but the bottom lift concrete used locally available, non-wear-resistant carbonate coarse aggregate. To obtain similar wear resistance in Alternative No. 1, the conventional design would have to use imported rhyolite coarse aggregate for all of the concrete in the pavement, adding cost and environmental burden.

In addition, Alternative No. 2 used a high-volume fly ash mixture for the cement-treated base (CTB), reducing the portland cement content significantly from what would be present in a conventional CTB as is used in Alternative No. 1.

Alternative No. 3 presents some additional changes that could have been used to improve the environmental footprint of Alternative No. 2 with no expected negative impact on pavement performance. Although the surface lift in Alternatives No. 2 and No. 3 were the same, the bottom lift in Alternative No. 3 was further optimized from an environmental perspective, replacing the locally extracted carbonate coarse aggregate with a recycled concrete aggregate obtained on site (note this requires that sufficient recycled concrete be available; transporting recycled concrete aggregates long distances actually would have negative environmental impact due to the required transportation). In addition, the amount of portland cement in the bottom lift was reduced from 548 lb/yd³ to 376 lb/yd³, and 94 lb/yd³ of fly ash was used, resulting in an overall reduction in the cementitious content in Alternative No. 3 compared to Alternative No. 2.

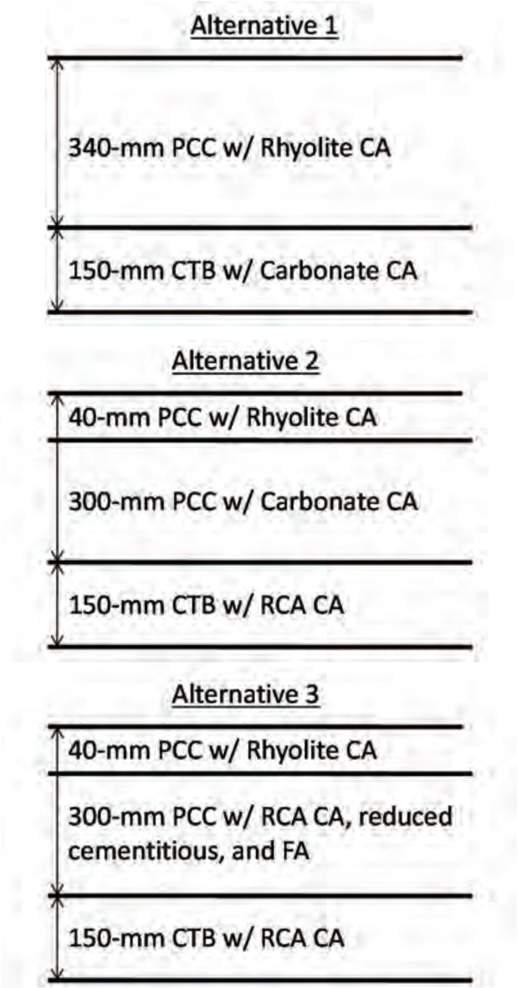

Figure 10.2 Three alternatives used in a limited LCA to determine environmental impact of design and material choices

In all cases, pavement performance over the life cycle was assumed to be identical for the three alternatives.

The LCA results for the three alternatives are presented in Figure 10.3. As is common with the presentation of the LCA results, they are normalized for each endpoint impact category with the worse performing alternative being set at 100 percent and the remaining alternatives presented as a percent reduction. For example, considering the global warming potential (GWP) of each alternative, Alternative No. 1 is the worst, Alternative No. 2 reduces the impact in this category to approximately 87 percent of Alternative No. 1, and Alternative No. 3 has a GWP impact that is approximately 65 percent of Alternative No. 1.

In all categories (other than non-hazardous waste), Alternative No. 1 is the poorest choice from an environmental perspective. Alternative No. 2 shows significant improvement (greater than 10 percent), and Alternative No. 3 shows even further improvement. It can be seen how such an analysis can be used in combination with design and materials choices to optimize a concrete pavement system, significantly lowering its environmental impact while ensuring equal or better long-term performance.

Table 10.1 Relevant Mixture Design Features in the Kansas Two-lift LCA Evaluation

Layer	Alternative No. 1	Alternative No. 2	Alternative No. 3
PCC Top Lift	This alternative had only a single PCC lift composed of the following: • 548 lb/yd³ cement • Imported rhyolite coarse aggregate	• 438 lb/yd³ cement • 110 lb/yd³ fly ash • Imported rhyolite coarse aggregate	• 438 lb/yd³ cement • 110 lb/yd³ fly ash • Imported rhyolite coarse aggregate
PCC Bottom Lift		• 548 lb/yd³ cement • Local carbonate coarse aggregate	• 376 lb/yd³ cement • 94 lb/yd³ fly ash • Recycled concrete coarse aggregate
Cement-Treated Base	• 172 lb/yd³ cement • Local carbonate coarse aggregate	• 78 lb/yd³ cement • 94 lb/yd³ fly ash • Recycled concrete coarse aggregate	• 78 lb/yd³ cement • 94 lb/yd³ fly ash • Recycled concrete coarse aggregate

Work continues to develop user-friendly LCA tools for use in considering the entire pavement life cycle. Once such tools are available, transportation agencies will have a mechanism to more fully consider the life-cycle impacts of design and materials choices.

3. Rating Systems

Currently, in an attempt to consider sustainable pavement practices, a number of rating systems are emerging. Rating systems will often use elements of the LCCA and LCA, integrated with other environmental and equity impacts, to assign points to alternatives in an attempt to assess overall sustainability. Two of the most widely known rating systems, GreenLITES and Greenroads™, are reviewed below, but there are a number of similar systems in existence and new systems continue to emerge, including the FHWA's INVEST Sustainable Highways Self-Evaluation Tool (www.sustainablehighways.org/) and the Institute of Sustainable Infrastructure's envision^{TM} rating system (www.sustainableinfrastructure.org/). Both of these are based on the Greenroads™ system.

GreenLITES

GreenLITES (Leadership in Transportation and Environmental Sustainability) was developed by the New York State Department of Transportation (NYSDOT) for the certification of project designs before they go to bid. The objectives of GreenLITES are the following (NYSDOT 2010):

- Recognize and increase "the awareness of the sustainable methods and practices already incorporated into the project design"
- Expand "the use of these and other innovative alternatives which will contribute to improving transportation sustainability"

A self-certification program, GreenLITES allows the project team to evaluate a project's sustainability before releasing it for bid. Based on evaluation of 26 recently completed designs, certification levels are scored and are given in Table 10.2.

Table 10.2 GreenLITES Certification Levels

Certification Level	Point Range	Percentile Range
Non-certified	0 – 14	< 33%
Certified	15 – 29	33 - 67%
Silver	30 – 44	67 - 90%
Gold	45 – 59	90 - 98%
Evergreen	60 and greater	98 and greater

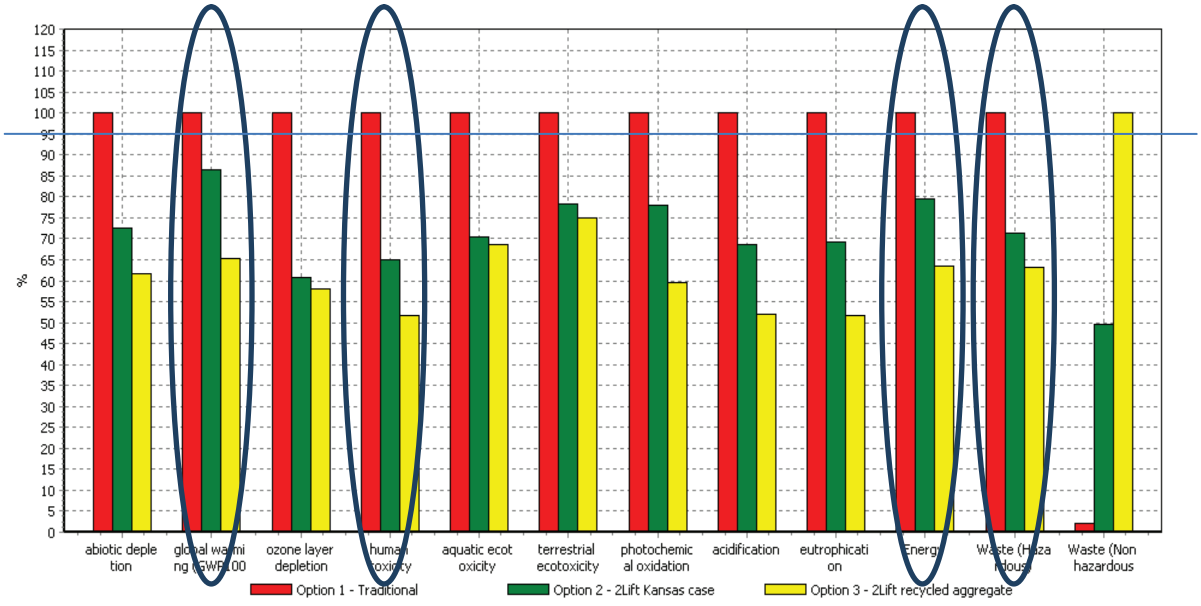

Figure 10.3 Results of the LCA of the three Kansas two-lift alternatives (from the Right Environment, Austin, Texas)

The project design elements are compared to the objectives and credit descriptions for each of the following five GreenLITES categories:

- Sustainable sites
- Water quality
- Materials and resources
- Energy and atmosphere
- Innovation/unlisted

Sustainable Sites

This category focuses on the location of the project and includes measures that can "protect and enhance the landscape's ability to regulate climate, provide cleaner air and water, and improve quality of life." This follows NYSDOT's policy to select the "best available alternative based on program / project goals and objectives, public involvement, and overall sustainability." The following subcategories are included:

- Alignment selection
- Context-sensitive solutions
- Land use/community planning
- Protect, enhance, or restore wildlife habitat
- Protect, plant, or mitigate for removal of trees and plant communities

Water Quality

This category seeks to protect bodies of water by "improving water quality and reducing storm water runoff." The design will be evaluated through the following subcategories:

- Storm water management including volume and quality
- Reduced run-off and associated pollutants by treating storm water runoff through best management practices (BMPs)

Materials and Resources

This category encourages the reduction of waste by reusing and recycling materials in beneficial ways and using local materials to the "greatest extent possible to minimize haul distances." The following subcategories are included:

- Reuse of materials
- Recycled content
- Locally provided material
- Bioengineering techniques
- Hazardous material minimization

Energy and Atmosphere

This category's goal is to minimize climate change impacts through energy conservation and efficiency. It supports air-quality improvement projects and encourages car pooling, mass transit, and non-motorized transportation. The subcategories included are the following:

- Improved traffic flow
- Reduced electrical consumption
- Reduced petroleum consumption
- Improved bicycle and pedestrian facilities
- Noise abatement
- Stray light reduction

Innovation/Unlisted

This category gives credit to designs that further GreenLITES strategies or to significant innovations in the project related to sustainability. Each agency is responsible for identifying what is important to them and will likely have different criteria.

Limitations

Many of the point categories lack specific amounts or levels of improvement required to receive the designated number of points; the points are followed by a list of items, and it is not clear how many of them are required to obtain the points. It is also unclear if the NYSDOT has specific improvement percentages or material use rates on which they will base the point rewards.

Specific examples of potential limitations related to use with concrete pavements include the following:

- *Re-use of materials (M-1 general)* – This does not include concrete mix designs which optimize alternative materials (such as fly ash, silica fume, etc.) to meet the pavement or structure requirements.
- *Reduce electrical consumption (E-2)* – This rewards projects that utilize low energy-consuming lighting equipment but doesn't mention the use of concrete pavements which may require less total lighting due to its reflectivity. Also, although the section is titled "Reduce Electrical Consumption," it does not consider electrical consumption during the extraction, manufacture, or construction phases for materials.
- *Reduce petroleum consumption (E-3)* – This includes project aspects that reduce petroleum consumption of the project including park-and-ride areas, public transportation connections, and design attributes that will limit maintenance fuel use. This item does not mention the reduction of vehicle fuel use by riding on concrete pavements. Also, although the section is titled "Reduce Petroleum Consumption," it does not consider petroleum consumption during the extraction, manufacture, or construction phases for materials.

Greenroads™

Greenroads™ attempts to measure performance of sustainable roadway design and construction. The performance metric was developed by a team headed by the University of Washington (UW) and CH2M HILL (Muench et al. 2011). The Greenroads™ program attempts to quantify the sustainable attributes of a roadway project and is a tool for the following:

- 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 Greenroads™ program has two major best-practice categories, mandatory and voluntary. Greenroads™ applies only to roadway design and construction. The mandatory best practices—Project Requirements—provide the minimum level of sustainable activities and each must be met as part of this metric. The voluntary practices—Voluntary Credits—are the optional attributes which show how the project has moved toward a truly sustainable endeavor.

For a roadway project to be evaluated, the project team overseeing the work will document how the Project Requirements have been met and which Voluntary Credits are being pursued. The Greenroads™ team verifies the application and the point totals and assigns the certification level. The levels include those shown in Table 10.3.

Project Requirements

The Project Requirements are as follow:

- Environmental review process, which requires the project team to perform an environmental review of the project
- Life-cycle cost analysis performed according to the Federal Highway Administration's Life-Cycle Cost Analysis in Pavement Design (FHWA 1998)
- Life-cycle inventory of final pavement design (reporting global warming potential and total energy only) using PaLATE v2.0 (Consortium on Green Design and Manufacturing 2011) or approved equal
- Quality control (QC) plan that lists responsibilities and qualifications of QC personnel and QC procedures during construction
- Noise mitigation plan needs to be established and implemented during construction

Table 10.3 Greenroads™ Certification Levels

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

- Waste management plan needs to be established and implemented during construction
- Pollution prevention plan for storm water that meets EPA Construction General Permit or local requirements, whichever is more stringent
- Low-impact development hydrologic analysis must be considered for storm water management in the right-of-way
- Pavement management system to maintain and operate a pavement including evaluation and documentation of preservation actions
- Site maintenance plan for roadway maintenance, storm water system, vegetation, snow and ice, traffic control infrastructure, and cleaning
- Educational outreach to the community as part of the operation of the roadway

Voluntary Credits

The optional Voluntary Credits are the attributes which show how the project has moved beyond the minimum requirements. There are 37 voluntary practices which are scored from one to five points each for a total of 108 points. Custom credits are available per the approval of the Greenroads™ program for up to an additional ten points. The voluntary credits are grouped into the following categories:

- Environment and water
- Access and equity
- Construction activities
- Materials and resources
- Pavement technologies
- Custom credit

The environment and water subcategories are as follow:

- Environmental management system
- Runoff flow control
- Runoff quality control
- Storm water cost analysis
- Site vegetation
- Habitat restoration
- Ecological connectivity
- Light pollution

The access and equity subcategories are as follow:

- Safety audit
- Intelligent transportation systems
- Context-sensitive solutions
- Traffic emissions reduction
- Pedestrian access
- Bicycle access
- Transit access and high-occupancy vehicle (HOV) access
- Scenic views
- Cultural outreach

The construction activities subcategories are:

- Quality management system
- Environmental training
- Site recycling plan
- Fossil fuel reduction
- Equipment emissions reduction
- Paving emissions reduction
- Water use tracking
- Contractor warranty

The materials and resources subcategories are the following:

- Life-cycle assessment
- Pavement reuse
- Earthwork balance
- Recycled materials
- Regional materials
- Energy efficiency

The pavement technologies subcategories are the following:

- Long-life pavement
- Permeable pavement
- Warm-mix asphalt
- Cool pavement
- Quiet pavement
- Pavement performance tracking

Greenroads™ custom credit subcategory "Recognize[s] innovative sustainable roadway design and construction practices."

Limitations

The Greenroads™ program recognizes some limitations in the system such as improvements in the upstream supply chain that may not be captured. For example, the production and manufacture of materials are not explicitly considered outside of the life-cycle inventories and assessments.

The Greenroads™ program also does not explicitly include additional roadway structures such as bridges, tunnels, walls, or other structures in the analysis. The program also does not explicitly include non-roadway structures such as luminaires, barriers, and walls. Nor does the program evaluate long-term maintenance beyond what is "planned" in various requirements and voluntary credits.

The long-life pavement credit does not accurately represent long life for either concrete or asphalt pavements, focusing exclusively on pavement thickness and ignoring the multitude of other design and construction details that truly produce pavements of long life. Further, it ignores regional and climatic differences which play a strong role in determining what contributes to long pavement life. Of particular concern from the perspective of the concrete paving industry is that according to the long-life pavement credit, for a lifetime equivalent single-axle load (ESAL) less than 500,000, the Greenroads™ program says that a 7-in. thick concrete pavement is equivalent to a 6-in. thick hot-mix asphalt (HMA) pavement. Over 50,000,000 ESALs, pavements qualify for the long-life pavement credit with 13 in. of concrete or 14 in. of HMA. The validity of this approach is highly questionable.

Specific examples of potential limitations related to use with concrete pavements include the following:

- *Life-cycle inventory (PR-3)* – The project team is required to complete the PaLATE Version 2.0 software tool for the project and report the total energy use and global warming potential in CO_2 equivalents. Other life-cycle software tools may be used if they output the total energy use and global warming potential by means of a transparent interface which clearly references data sources. Overall, more impacts than just energy and CO_2 should be reported in a life-cycle inventory.
- *Light pollution (EW-8)* – This category rewards projects that use lamps that prevent light pollution but doesn't mention the use of concrete pavements, which may require less total lighting due to its reflectivity.
- *Paving emissions reduction (CA-6)* – Although this category is a benefit to worker safety and the environment around HMA paving operations, it may be appropriate for concrete paving operations to receive points because they do not have these air emissions that need to be controlled. Greenroads should be encouraged to allow an alternative for which concrete pavements can earn credit.
- *Energy efficiency (MR-6)* – This category rewards projects that use low energy consuming equipment but doesn't mention the use of concrete pavement, which may require less total lighting due to its reflectivity.

4. Summary

Assessing pavement sustainability is an essential element in making pavements more sustainable, as it is well known if something is not measured, it will not get done. Although the concept of assessing sustainability is not difficult, in practice, it is very complex. The use of LCCA to determine life-cycle economic costs is a mature and accepted approach to compare alternative pavement designs. Environmental impacts can be assessed using an LCA, but readily accessible tools are not available, and gaps in the data and knowledge limit this approach at the current time.

Emerging pavement sustainability rating systems provide a means to currently assess pavement sustainability, but limitations that exist in these systems mean that they should be used to help guide users in making their practices more sustainable but should not be used in absolute terms to determine which pavement alternative is more sustainable compared to another. These tools should be used to advance the state of the practice, not for material approval or selection.

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Chapter 11

CONCLUSIONS AND FUTURE DEVELOPMENTS

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Are pavements perfectly sustainable? No. Like any other infrastructure system, their construction and maintenance consume nonrenewable resources, generate waste, and consume energy. More significantly, users of modern vehicles have a significant negative environmental and social impact as they travel on any pavement, with respect to such aspects as energy consumption, emissions, and noise. Pavements also interact directly with the environment and society, impacting such things as local temperatures and surface run-off.

On the other hand, modern civilization would be inconceivable without the ability to move goods, people, and expertise quickly and affordably over large distances via surface transportation.

Therefore, to establish a more sustainable pavement system, both the negative and positive economic, environmental, and social impacts must be considered and alternatives sought that minimize the negative while maximizing the positive. Fundamental to advancing sustainability is the need to identify the parameters critical to success and understand how these parameters may be modified in such a way that significant and continued improvement can be achieved.

In this regard, concrete pavements have a good story to tell, as they have been effectively used for generations to support economic and social good over the life cycle and provide many opportunities for further improving their sustainability in the future.

The first 10 chapters of this publication define sustainability concepts and how they may be considered when designing, building, and maintaining concrete pavements. They also identify a number of easily implementable strategies that can be employed to improve the sustainability of concrete pavements, plus the parameters and tools for measuring these improvements. This chapter briefly summarizes this information and provides an overview of innovative approaches.

1. Review

Sustainability-related concepts related to pavements can be applied in practical and holistic ways in every stage of a concrete pavement: design, materials selection, construction, use, renewal, and end-of-life recycling. Urban environments provide unique opportunities for implementing concrete pavement solutions that enhance sustainability. Determining the success of these strategies requires a systematic approach to selecting and measuring performance criteria.

Pavement Sustainability Concepts

To date, decision making by pavement professionals has largely been based on consideration of the bottom-line, which was understood in purely economic terms. To advance sustainability, the bottom line must be expanded to include environmental and societal terms. Sustainability is also much broader than the application of a number of individual activities but needs to be approached system-wide.

Essential to understanding sustainability is an understanding of how the current consumption-based industrial system negatively impacts social systems. The concept of a regenerative, circular economy should be adopted, along with greater use of renewable resources and a reduction in accumulating waste. Ideally, the system will ultimately mimic nature, in which the concept of waste is eliminated and all waste becomes raw material for another process.

Sustainability also requires the adoption of a life-cycle perspective, in which the economic, environmental, and social benefits and costs of any product or service are considered over its entire life, requiring a cradle-to-cradle approach in which the end of life is part of a new beginning.

Designing Sustainable Concrete Pavements

Sustainability is not an accident. Design plays a very strong role in ensuring that the constructed concrete pavement begins its life with sustainability in mind, which requires a thoughtful approach to the design of the whole pavement. The designer must follow several principles:

- Account for human needs and values while considering the environmental setting in which the pavement will be constructed.
- Make engineering decisions that will ensure that the pavement will perform as desired for the intended life (likely 40 years or more). Design features of long-life concrete pavements include the following:
    - Adequate thickness
    - Strong, erosion-resistant bases
    - Doweled transverse joints, or continuously reinforced concrete pavement where volume of traffic requires them
    - Appropriate materials and proportioning for durability, economy, and reduced environmental impact
    - Timely maintenance and rehabilitation
- Choose systems and approaches that will have minimum economic, environmental, and social cost, without compromising engineering quality.
- Design for what is needed. Overdesign is wasteful, but under-design is even more wasteful because longevity of the system may be compromised.
- Consider the impact of alternative approaches and conduct sensitivity analyses.

Innovation that meets these goals should be encouraged.

Selecting Materials

The materials used in making paving concrete have a significant impact on the sustainability of the pavement because their production and transport to the site have relatively large impacts and they directly impact long-term performance.

Manufacturing portland cement is an energy intensive process that requires crushing, grinding, and heating raw materials and grinding the clinker at the end of the process. It also has a high CO_2 burden, as the decomposition of calcium carbonate ($CaCO_3$) rock into calcium oxide (CaO) and CO_2 is an inherent part of the process. The environmental burdens associated with a concrete pavement can be reduced by any combination of five actions:

- Make the manufacturing process more efficient
- Reduce the amount of portland cement clinker in the cement
- Reduce the amount of cement in the concrete mixture
- Use less concrete in a pavement over the life cycle
- Extend the useful life of the pavement

SCMs are common byproducts from other industries that beneficially react with portland cement to enhance long-term performance. Thus, the effective use of SCMs not only reduces the amount of portland cement required, it also reduces the need to dispose of what otherwise would be industrial waste. This is often done at reduced economic cost.

Aggregates comprise the bulk of the volume of a concrete mixture and generally have the lowest environmental impact. Creating a desired aggregate grading and using as large a nominal maximum aggregate size as practical for a given situation will allow the reduction of the amount of cementitious materials required in a mixture. In general, aggregates have limited direct impact on the durability of a mixture except for D-cracking and AAR, which can be avoided through material testing and application of mitigation strategies.

Recycled concrete and other construction waste can be used as aggregates in paving concrete and supporting layers, reducing the demand for virgin aggregates and also reducing the need to place the waste materials into landfills.

Chemical admixtures are used in small quantities; therefore. their direct environmental impact is small. Their overall impact, however, is large, as they can be used to significantly reduce the amount of cementitious material required to achieve performance, and they can markedly improve potential durability of a mixture.

The goal of mix proportioning is to find the combinations of available and specified materials that will ensure that a mixture is cost effective, meets all required performance requirements, and does this at the lowest environmental and social cost over the life cycle. In the case of sustainable design, reducing the life-cycle environmental footprint (e.g., embodied energy and GHG emissions) must be one of the performance requirements considered.

Construction

The construction phase is of relatively short duration when compared to the total life of a concrete pavement. However, initial construction quality has a significant influence on the concrete pavement's service life, which in turn directly impacts life-cycle economic, environmental, and social costs. What may be intended to be a sustainable pavement through enhanced design and optimized material selection can turn out be be non-sustainable due to improper construction processes and/or a lack of quality control which leads to premature failure.

The energy consumed during construction also needs to be considered as well as the environmental and societal impacts incurred during the construction phase. Construction processes and equipment should be optimized to minimize fuel consumption and emissions. Environmental and societal impacts associated with the construction phase include the following:

- Erosion and storm water runoff
- Emission of CO_2 and particulates through equipment exhaust stacks
- Emission of airborne dust particulate from construction processes
- Noise generated from construction processes
- Slurry run-off from wet sawing joints
- Increased road user cost due to traffic delays caused by construction

The Use Phase

The use phase, particularly the traffic using the facility, has the largest life-cycle impact on the environment. These impacts include not only energy consumption and emissions but also noise, run-off, and temperature.

Vehicle fuel consumption depends on many factors that are the same regardless of pavement type. However, pavement roughness, surface texture, and stiffness can be controlled by the managing agency, which has the ability to design, construct, and maintain a pavement surface that will minimize the economic, environmental, and social impact of vehicle operations.

Other use phase factors that warrant consideration include solar reflectance, lighting needs, long-term concrete carbonation, water run-off, and traffic delays.

Pavement Renewal

Preservation and rehabilitation play an important role in ensuring pavement longevity while maintaining an acceptable level of serviceability. Long-lasting pavements reduce future investment in new materials and construction, thus minimizing economic, environmental, and social impact over the life cycle. A well maintained concrete pavement will remain in a smooth, safe, and quiet condition for a greater duration of its life, thus increasing the fuel efficiency of vehicles, reducing crashes, and minimizing social impact due to noise.

Renewal strategies that can be applied to concrete pavements to maintain serviceability over the design life include preventive maintenance and rehabilitation. Preventive maintenance is a planned strategy employing treatments that extend pavement life generally without increasing structural capacity. Pavement rehabilitation adds some structural capacity, usually through the application of additional pavement thickness in the form of an overlay.

Initially, pavement condition decreases slightly with time as the pavement ages and is subjected to traffic. If left unattended after this initial phase of the pavement life, performance decreases at an increasing rate before finally leveling off once it has reached a poor condition. Preventive maintenance is applicable during the initial phase when the pavement is in relatively good condition and has significant remaining life. Pavement rehabilitation is appropriate once the pavement condition has dropped to a point where it is no longer effective to apply preventive maintenance. Reconstruction is ultimately the only suitable alternative once the pavement condition has dropped below a given level.

End of Life

At the end of life, a concrete pavement should be completely recycled. The ultimate goal of recycling is to develop a zero waste stream utilizing all byproduct materials in the rehabilitation or reconstruction of a concrete pavement. Not only is this economically advantageous, local recycling minimizes environmental impact by reducing the carbon footprint, embodied energy, and emissions as well as enhancing social good by reducing the need for landfills and the extraction of nonrenewable raw materials. The concept of recycling must be viewed as a cradle-to-cradle undertaking.

An added benefit of recycling concrete is the potential to reduce atmospheric CO_2 through carbon sequestration, or carbonation. Typical environmental conditions in a pavement subsurface base system are favorable for accelerated carbon sequestration, thus recovering up to 50 percent of the CO_2 released during cement manufacturing.

Hydraulic cement concrete can easily be processed into RCA which has added value as an aggregate replacement in new concrete, as a dense graded base material, as drainable base material, and as fine aggregate. The quality of RCA concrete depends primarily on the amount of mortar that remains attached to the original aggregate. The mechanical properties of RCA are a function of the quality and size of the particles. Generally RCA can be processed to have more than adequate values of abrasion resistance, soundness, and bearing strength.

Urban Environment

The infrastructure needs of densely populated urban areas are significant. The include pavements, sidewalks, water and sewer utilities, and power transmission lines. Such systems are extremely sensitive to disruption, which can have large social impacts when natural or manmade disasters occur. Pavements represent a key element in this infrastructure. Traffic congestion and delays, smog, safety concerns, and even aesthetics play a greater role in urban areas because any impact has the ability to affect a larger segment of the community and the environment as a whole. Thus, potential strategies that may be cost prohibitive in a rural location may now become cost effective, and strategies that would not have been considered before may now be applicable when the societal impacts are considered.

One such example is the heat island effect, which occurs where there is a local area of elevated temperature located within a region of relatively cooler temperatures. Because of the greater density of paved and covered surfaces in urban environments, the heat island effect occurs most frequently in urban areas. The effects of urban heat islands are broad, not only resulting in increased levels of discomfort but also occasionally having an impact on human health. One strategy for mitigating the urban heat island effect is using reflective paving materials, including conventional concrete. Additives that can further increase the SRI of concrete, such as slag cement or light-colored fly ash, are also recommended.

There are additional benefits in using light-colored concrete pavements. Light-colored pavements can also improve safety by improving night visibility while reducing artificial lighting requirements, thus saving energy and reducing emissions. In urban environments, photocatalytic cements and/or coatings may be a viable option to help maintain highly reflective surfaces.

Precipitation runs off hard, impermeable surfaces (such as pavements) much faster than off undeveloped or vegetated ones. The concern from the standpoint of environmental impact is that storm water systems will be overwhelmed when large areas of vegetation are replaced with paved or hard surfaces, resulting not only in flooding but also in erosion and the transport of pollution into nearby surface waters. Typical storm water management techniques, such as retention ponds, are difficult to implement in urban areas due to lack of available land. Thus, sanitary sewers often are used to handle storm water, thus resulting in increased needs for water treatment and/or release of untreated water. For these reasons, innovative pavement solutions are acutely needed in urban areas, including the use of pervious concrete pavement surfaces.

Assessment

It is essential that the sustainable features of pavements be assessed and quantified to recognize improvement and guide innovation. Many product and service manufacturers make claims about the sustainability or "greenness" of their products and processes. It can be difficult for an owner, agency, consultant, contractor, or specifier to sort through these claims without an accurate, repeatable, and objective system to assist them in their selection. In order to make the most informed design decisions with regard to sustainability, decision makers must employ a tool or tools that allow comparison of different design choices.

No one tool is currently available that simultaneously considers economic, environmental, and societal impacts. Economic impacts are often assessed separately through life-cycle cost analysis (LCCA). Environmental impacts can be examined through a life-cycle assessment (LCA). Tools to assess societal impacts are still in their infancy.

To address this need, a number of pavement sustainability rating systems are emerging. Rating systems will often use elements of the LCCA and LCA, integrated with other environmental and societal impacts, to assign points to alternatives in an attempt to assess overall sustainability.

2. Innovation

Dramatic improvements in concrete pavement sustainability will require the adoption of innovations. Some innovative approaches have been used in demonstration projects and show promise for implementation. Others still require research.

Several technologies have been adopted in response to implementing sustainability principles. These include the following:

- Changes in cementitious materials systems and mixture proportioning
- In-situ concrete recycling
- Recycling water at the concrete plant
- Pervious concrete
- Next generation quiet texturing
- Precast paving units

Technologies at the demonstration stage include the following:

- Two-lift construction
- Photocatalytic cements
- Inclusion of RAP in concrete mixtures
- Bubbling cement plant exhaust gases through pools to grow algae from the CO_2, which is then dried and burned in the kiln as fuel

Further advances are just over the horizon:

- Low-carbon to carbon-sequestering cements
- Alternative sources of raw materials for portland cement manufacture that will not involve the decomposition of carbonate rock
- Energy efficient devices to convert CO_2 to solid carbon fiber, including carbon nanotubes
- Processes to capture mercury in the cement manufacturing process
- Mixtures that have self-healing capabilities
- Smart pavements that monitor their condition and report when they are getting stressed
- Pavements that generate electricity to power adjacent neighborhoods
- Geothermal heat under the pavement being captured to melt snow
- Pervious shoulders with bacteria in them that will treat water as it travels through the pavement

Specifications and contractual systems need to be developed and implemented that will encourage implementation of promising approaches. Coupled to this is a great need to educate and train designers and practitioners. There is plenty of challenging, exciting work yet to be done.