

## CHAPTER 4. PAVEMENT AND REHABILITATION DESIGN TO IMPROVE SUSTAINABILITY

### Introduction

This chapter describes sustainability considerations in the design of both new and rehabilitated pavement structures, with the latter including structural overlays and reconstruction. The first step in pavement design is to define the objectives based on the goals and policies of the owner/agency, which should include sustainability objectives. The design process results in the development of alternative pavement structures (including structural layers and thicknesses), specifications for materials that meet the performance objectives of the individual layers as well as the system as a whole, considerations for subsurface drainage (as appropriate), and governing construction specifications needed for the pavement to perform as intended.

As described in chapter 2, all pavement types can be designed to be more sustainable by considering costs, environmental impacts, and social needs together. This is true even for pavements built with relatively conventional materials and construction techniques, but as noted in chapter 2 it is up to the owner/agency to set the goals and establish the considerations that will receive greater emphasis in the development of “more sustainable” pavement designs.

In particular, this chapter reviews the decisions made in the design process (e.g., layer type options, materials, thicknesses, appropriate layer combinations, and geometric features) that can affect the overall sustainability of the resulting pavement, with a focus on pavement types, specific materials, and structural design considerations. The objective of the chapter is not to present innovative pavement designs but rather to communicate the need to critically evaluate the entire design process in order to make the pavement that is ultimately designed the most sustainable option for the stated design objectives and constraints.

The scope of this chapter, relative to several other related chapters, is shown in table 4-1. It is observed that, in addition to new and reconstruction design, this chapter includes structural overlays (both asphalt and concrete) as they require a design component (considering the existing pavement condition and future traffic levels) that leads to the provision of additional load-carrying capacity. Nonstructural overlays and pavement maintenance and preservation treatments are covered in chapter 7, and specific end-of-life strategies (e.g., full-depth reclamation, recycling) are covered in chapter 8.

The selection of alternate routes or alternative modes of transportation are outside the scope of this document. The design and construction of new geometry for roads, including consideration of the impacts of horizontal and geometric alignment on construction activities (e.g., excavation, material movement, tunneling, balancing of cut and fill) and vehicle operations (e.g., effects of vertical and horizontal curves on fuel economy, other vehicle operating costs and safety) are also outside the scope of this document. Research by various organizations over a number of years has identified the effects of road geometry on vehicle fuel consumption, other vehicle operating costs, and safety (see, for example, Claffey 1971; Watanatada et al. 1987, and Ko, Lord, and Zietsman 2013, among others). The net effects of environmental impacts considering earthworks and materials to construct different geometric designs, as well as the benefits from improved vehicle operating cost in the use phase, can be evaluated through LCA.

Table 4-1. Division of scope between design, maintenance and preservation, and end-of-life chapters.

Pavement Type	Chapter 4. Pavement and Rehabilitation Design to Improve Sustainability	Chapter 7. Maintenance and Preservation Treatments to Improve Sustainability	Chapter 8. End-of-Life Considerations
<b>Asphalt Pavements</b>	<ul style="list-style-type: none"> <li>• New Asphalt Pavement Design or Reconstruction</li> <li>• Structural Asphalt Overlay</li> <li>• Bonded Concrete Overlay</li> <li>• Unbonded Concrete Overlay</li> </ul>	<ul style="list-style-type: none"> <li>• Crack Filling/Sealing</li> <li>• Asphalt Patching</li> <li>• Fog Seals/Rejuvenators</li> <li>• Chip Seals</li> <li>• Slurry Seals</li> <li>• Microsurfacing</li> <li>• Ultra-thin and Thin Asphalt Overlays</li> <li>• Hot In-Place Recycling</li> <li>• Cold In-Place Recycling</li> <li>• Ultra-thin Bonded Wearing Course</li> <li>• Bonded Concrete Overlays</li> </ul>	<ul style="list-style-type: none"> <li>• Central Plant Recycling</li> <li>• Full-Depth Reclamation</li> </ul>
<b>Concrete Pavements</b>	<ul style="list-style-type: none"> <li>• New Concrete Pavement Design or Reconstruction</li> <li>• Bonded Concrete Overlay</li> <li>• Unbonded Concrete Overlay</li> <li>• Structural Asphalt Overlay               <ul style="list-style-type: none"> <li>– Conventional</li> <li>– Crack/Break Seat</li> <li>– Rubblization</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Joint/Crack Sealing</li> <li>• Slab Stabilization/Slab Jacking</li> <li>• Diamond Grinding/Grooving</li> <li>• Partial-Depth Repairs</li> <li>• Full-Depth Repairs</li> <li>• Dowel Bar Retrofit</li> <li>• Slot/Cross Stitching</li> <li>• Ultra-thin Bonded Wearing Course</li> <li>• Bonded Concrete Overlays</li> </ul>	<ul style="list-style-type: none"> <li>• Concrete Recycling               <ul style="list-style-type: none"> <li>– In Place</li> <li>– Off site</li> </ul> </li> </ul>
<b>Other Pavement Types</b>	<ul style="list-style-type: none"> <li>• New Composite or Semi-rigid Concrete</li> <li>• Pavement Design or Reconstruction</li> <li>• New Drivable Pavement Design or Reconstruction</li> <li>• New Modular Pavement Design or Reconstruction</li> </ul>		

### Pavement Design Considerations

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

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

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

The following are items that may be included in project-specific requirements for the design of a particular pavement:

- Expected design life.
- Smoothness.
- Surface texture as it impacts friction and noise.
- Splash/spray.
- Stormwater runoff.
- Traffic delay associated with future maintenance.
- Reliability considering cost and level of interruption of service for maintenance and future rehabilitation.
- Ability to accommodate utility installation and maintenance.
- Potential for future obsolescence (the pavement will need to be replaced or removed before its design life is reached).
- Local thermal environment as influenced by pavement.
- Aesthetics.

Each of these considerations can have an impact on the sustainability of the pavement, but their relative importance will depend on the context of the design as well as the overall sustainability goals of the owner/agency and the specific project objectives. Each requirement should be assessed by the designer based on how the pavement will interact over its entire life cycle with users (both for passenger mobility and freight movement, where applicable, and primarily in terms of safety and efficiency), the surrounding community, and the environment (both local and global effects). The requirements of the users and community will also depend on the functional class of the roadway, and may also vary with time. Similarly, the overall benefits of different design approaches to improving sustainability will depend on the context of the design (such as location, traffic volumes and characteristics, support conditions, climatic conditions, and so on) and will also likely vary with time (Santero and Harvey 2010).

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

- Surface performance.
  - Smoothness is often considered the most important surface characteristic; texture and deflection may also be considerations (see chapter 6 for details).

- The pavement surface affects vehicle fuel consumption (see chapter 6 for details), vehicle life, and freight damage costs.
- The consideration of future maintenance and rehabilitation and their effects on smoothness are important components to be considered in evaluating sustainability impacts.
- Surface performance is context sensitive in that it is very critical to pavements exposed to higher traffic volumes and less important to pavements carrying lower traffic volumes. For pavements carrying heavy traffic volumes, the environmental benefits of keeping the pavement smoother can far outweigh the negative environmental impacts of materials production and construction.
- Design life selection.
  - The functional and structural life of the pavement is influenced by both traffic and environmental factors.
  - The selection of the design life should include the consideration of higher initial economic costs and environmental impacts associated with longer life designs versus higher future costs and environmental impacts associated with shorter life designs (due to the need for additional maintenance and rehabilitation activities).
  - The selection of the design life should include consideration of end-of-life alternatives (see chapter 8).
- Pavement type selection.
  - The pavement type selection impacts every phase of the pavement life cycle, including the selection of initial materials and construction as well as the future maintenance and rehabilitation, use phase, and end of life.
  - The relative sustainability impacts of different pavement types depend on location, design traffic, and available materials.
- Construction and materials selection.
  - The impacts of materials selection on sustainability depend on the local sources of materials and the transportation alternatives available (see chapter 3 for details).
  - The ability to achieve quality construction with available materials and construction equipment and expertise impacts the sustainability of the pavement (see chapter 5 for details).
  - Traffic delays in construction work zones may result in negative sustainability impacts where traffic volumes are high and traffic management plans (TMP) cannot mitigate delay; slowing traffic down may lead to small improvements in the sustainability impact.
- Construction quality requirements (see chapter 5 for details).
- Recycling strategies (see chapters 3 and 8 for details).

The impact on pavement sustainability that results from these types of decisions can be assessed through LCA and through sustainability ratings systems as part of an overall assessment process (see chapter 10 for details on these processes).

### Consideration of Payback Time

One approach to evaluating whether sustainability goals are being met is the concept of “payback time.” Payback time is defined as the period between the initial environmental impact and the time to achieve a zero difference compared to the standard approach, after which there is a net reduction in environmental impact; more simply, it is the time required to recoup the benefits (be they cost, environmental, or social) associated with a pavement design investment. This concept is useful when evaluating design approaches that require a larger initial cost or environmental impact as compared with standard practice, but which provide significant impact reductions over the rest of the pavement life cycle. Some typical examples involve long-life pavement designs, which increase the time (years) before the first rehabilitation or reconstruction, reduce the level and frequency of maintenance during the life, and keep a pavement smoother over its life, but will likely have a higher initial impact on cost and the environment because of the use of premium or unique materials or increased layer thicknesses. A payback analysis provides an indication of the uncertainty of achieving a reduction in environmental impact over the life cycle due to a design decision, with longer payback times have greater uncertainty regarding the ability of the assessment to accurately quantify them and whether they will actually occur.

An example of the payback time for a specific case study is provided in figure 4-1, which shows a comparison of the GWP of the materials production and construction phases for pavements with 20-, 40- and 100-year design lives (all using the same materials). It can be seen that the 40-year pavement initially has more GWP than the 20-year pavement, primarily due to a thicker structure, but that the difference is made up after 29 years; furthermore, over a 100-year analysis period the 40-year pavement has approximately half the GWP of the 20-year pavement.

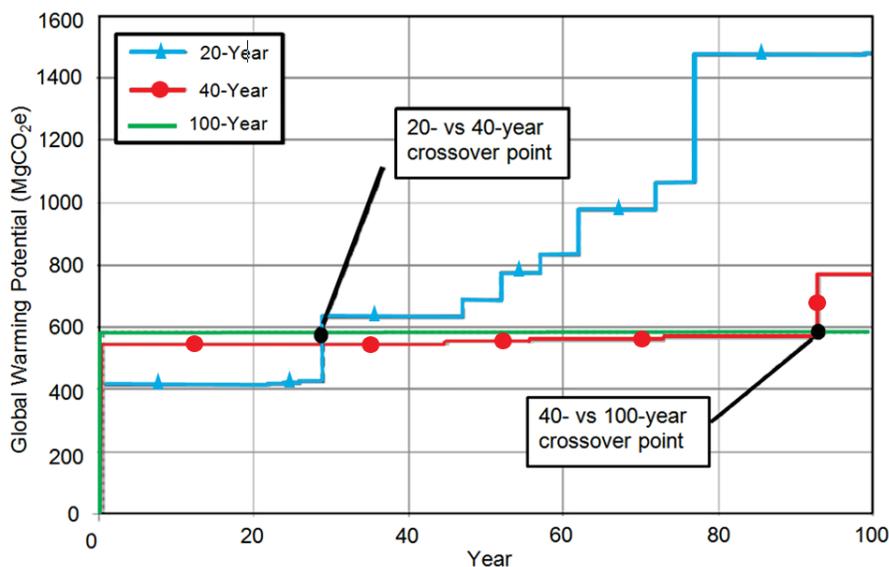


Figure 4-1. Example of payback time analysis considering only the material production and construction phases of three different pavement design lives (modified from Santero, 2009).

As noted previously, longer payback times indicate greater uncertainty in the final difference between alternatives. For example, it can be seen in figure 4-1 that the payback time (cross-over point) is 93 years between the 40- and 100-year design lives, and that the actual difference in initial GWP between those two alternatives is small. Longer payback periods also mean that the

### **AASHTOWare Pavement ME Design Software**

*The AASHTO mechanistic pavement design procedure (AASHTO 2008) and the accompanying AASHTOWare Pavement ME Design software (AASHTO 2012) are based on mechanistic-empirical design principles and provide a powerful tool for pavement engineers to predict pavement performance. Pavement ME considers different pavement types, layer types and thicknesses, material properties, traffic projections, and climatic data. It allows users the ability to evaluate multiple pavement designs over a specified analysis period and match future maintenance and rehabilitation needs with the predicted distresses. From the user defined layer types, properties, and general inputs, the software determines the minimum pavement surface thickness based on project and agency objectives and selected failure criteria. The Pavement ME software can also be used for forensic investigations to study the deficiencies associated with existing pavements.*

*The AASHTO Pavement ME is calibrated at the national level, and thus local calibration of the distress models may need to be completed; furthermore, particular scrutiny may need to be given to designs utilizing innovative designs, materials, and construction not part of the distress model calibration.*

planet and humans are exposed to the environmental impact for an extended period before any environmental benefit is realized, although societal and economic impacts may occur. The example shown in figure 4-1 only considers the impacts of material production and construction, and consideration of use phase impacts will likely change the cross-over point. Approaches for considering the time dependency of impacts in LCA and carbon footprints are being developed (Kendall, Harvey, and Lee 2009; Harvey et al. 2010; Kendall 2012).

### Mechanistic-Empirical Design Methods

Empirical pavement design methods, which are based on observations of the performance of in-service pavements without consideration of theoretical concepts of pavement behavior, can only consider how pavements perform within the narrow realm of the prevailing conditions (e.g., fixed material types, fixed pavement types and design features, fixed environmental conditions and traffic loadings). This design framework makes it more difficult to introduce innovative materials, designs, and specifications without constructing full-scale test sections and observing performance.

Mechanistic-empirical (ME) design methods offer much greater opportunity to consider alternative materials, pavement structures, and construction procedures. For both conventional and new paving materials, ME design directly considers key material properties (such as stiffness, fatigue resistance, low-temperature cracking properties, permanent deformation resistance, and thermal expansion) and is able to relate those properties directly to pavement performance through available response and performance models. ME design allows the

development of designs even for new materials that have not been used before, based on their predicted mechanistic (the “M” in ME) response to traffic loads, temperatures, and moisture condition. The performance predictions can be improved as more empirical (the “E” in ME) performance data become available. Similarly, ME design permits the evaluation of changing construction specifications through consideration of their effect on input materials properties.

ME design can estimate key asphalt or concrete pavement distresses (such as cracking, rutting, faulting) and roughness (e.g., International Roughness Index [IRI]) versus time, which allows the designer to consider alternative trigger levels for maintenance and rehabilitation. ME design tools also allow the designer to analyze alternative decisions that will affect many of the factors in the pavement life cycle that are shown in figure 2-1 in chapter 2.

The AASHTOWare Pavement ME Design Software (see sidebar) uses an iterative process, with the designer calculating the expected performance of a proposed structure, and then changing aspects of the design to move towards design objectives, such as structural and functional performance levels, cost stipulations, and geometric constraints, but these objectives can also include environmental and societal impacts. The AASHTO Pavement ME is a tool for determining the pavement type and corresponding layer types and thicknesses for a wide range of new and rehabilitated pavement structures. Some state DOTs have developed and are using other ME design procedures and software tools (e.g., California, Minnesota, Texas) for different types of pavements and some states are using Pavement ME or other ME tools in combination with empirical procedures. There are also ME design tools available from industries, organizations, universities, and other countries that are too numerous to provide a comprehensive list of citations. All ME procedures including the AASHTO Pavement ME Design have various advantages and limitations in terms of models, extent of calibration, local applicability with regards to materials and environment, availability of input data, and ability to consider new pavement and rehabilitation alternatives such as many of those discussed in this document. Any ME procedure should be evaluated before it is used, and the results used with care by an experienced pavement designer.

### **Process for Consideration of Sustainability in Pavement Design**

An example of an overall process for considering sustainability in pavement design is shown in figure 4-2. The process shown in the figure is particularly oriented towards the design-bid-build (i.e., low-bid) project delivery process.

There are numerous alternative pavement solutions that can be proposed for any set of design requirements. The pavement design process, whether asphalt, concrete, modular, or composite, must begin by defining the owner/agency design and policy objectives as well as any sustainability objectives. Once various pavement design alternatives have been developed, LCCA, LCA, and pavement rating tools can be applied to assess economic, environmental, and societal impacts to varying degrees as a way of improving the sustainability aspects of the proposed pavement designs. Chapter 10 provides additional information on those assessment tools.

### **Design Objectives**

An owner/agency has a number of different objectives to consider when developing a pavement design. These may be explicit objectives included in policy, may be implicit to the local agency, or may be just emerging.

### ***Performance Objectives***

The overall performance objectives used in the design process will depend on agency policies. These policies are typically developed based on a number of items, such as acceptable distress and ride quality levels and economic analyses of agency initial and life cycle costs, and may also include some types of road user costs and funding agency guidelines.

In a design-bid-build (DBB) or design-build (DB) project delivery environment, it is assumed that the design methodology will adequately predict the ability of the constructed pavement to meet the performance objectives. Some examples of performance objectives in the DBB or DB delivery environment include:

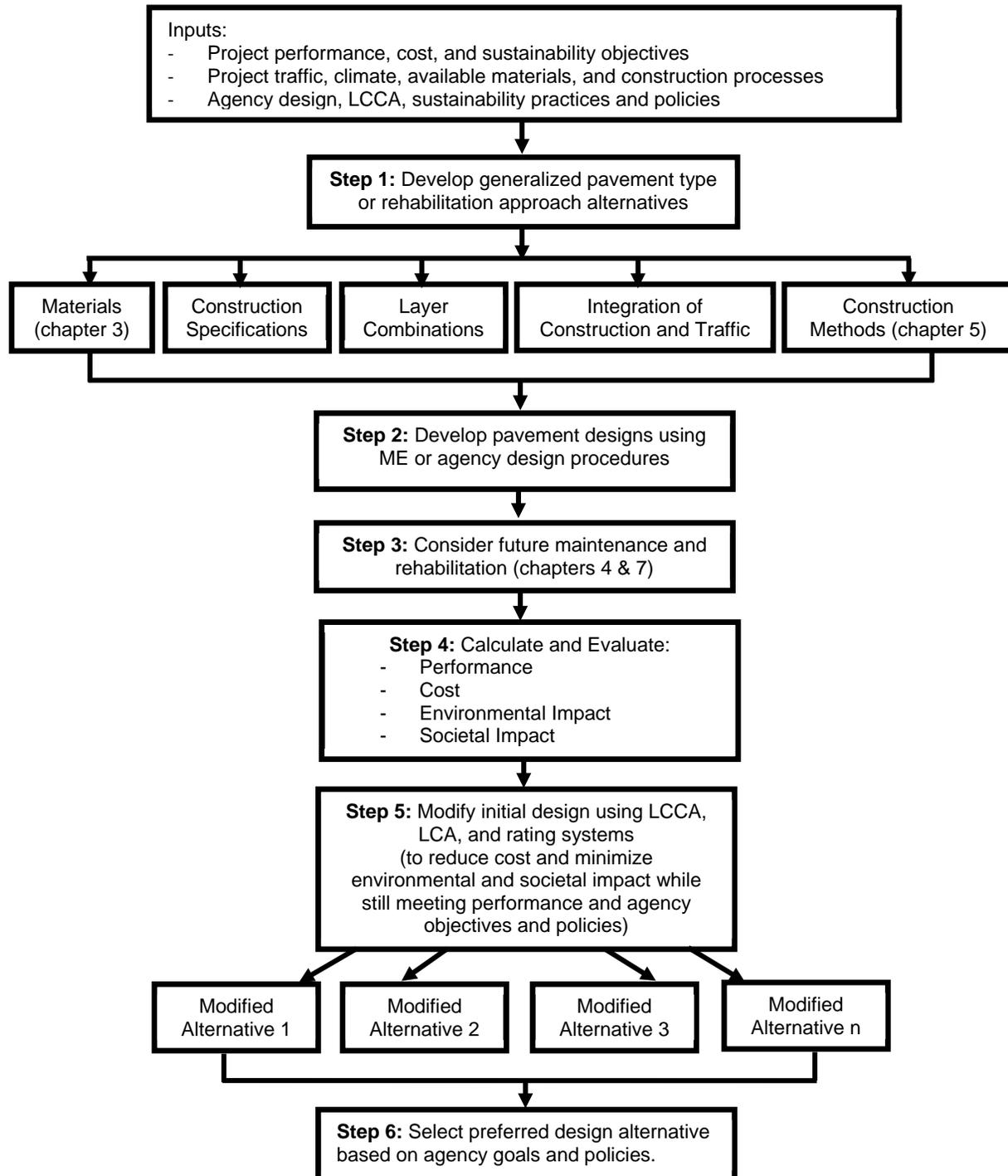


Figure 4-2. Overall process for considering sustainability in pavement design.

- Design life, or the number of years it takes to reach the defined end of life based on the effects of the predicted traffic loading and climatic impacts on the assumed pavement structure.
- Reliability, or the probability of reaching the design life before exceeding established distress or ride quality thresholds.

In a design-build-maintain (DBM) project delivery environment, performance objectives are explicitly written as contractual performance requirements that the contractor must deliver during the contract performance period. Some examples of performance requirements for DBM include:

- Maximum allowable IRI.
- Maximum amount of cracking or other indicators of structural deterioration.

### *Cost Objectives*

It is common for an agency's cost objective to be to minimize the overall life-cycle cost of the pavement over a defined analysis period, or it may be to minimize the life-cycle cost while also operating within an initial cost constraint. Additional guidance on LCCA is found in chapter 10, with detailed information available from the FHWA (Walls and Smith 1998). The General Accounting Office has recently reviewed a sample of state LCCA practices and provided recommendations for improvements (GAO 2013).

### *Sustainability Objectives*

Chapter 2 lists in detail the potential sustainability goals and objectives that are inherent as part of the pavement design process. This includes not only meeting the performance goals and cost requirements, but also minimizing environment impacts and meeting key societal needs.

### Alternative Pavement or Rehabilitation Types

After the goals and policy objectives of the owner/agency have been defined, the project traffic and climate data have been compiled, and available materials and construction processes have been determined, the next step is the development of various pavement design alternatives. There are a variety of new and rehabilitated pavement structures that can be considered, broadly grouped into the following categories: asphalt pavements (including asphalt overlays), concrete pavements (including concrete overlays), composite pavements (asphalt over concrete and two-lift concrete on concrete), modular pavements, and fully permeable pavements. These are described in the following sections.

### *Asphalt Pavement Types*

#### *New or Reconstructed Asphalt Pavement Structures*

As described in chapter 1, asphalt pavements are those with an asphalt surface layer of any thickness (even including only a chip seal), and may include various asphalt stabilized structural layers. They may also include granular support layers (bases and subbases) below the asphalt bound layers and above the subgrade. Full-depth asphalt pavements include only an asphalt surface and binder course layers paved on treated or compacted subgrade, as illustrated in figure 4-3.

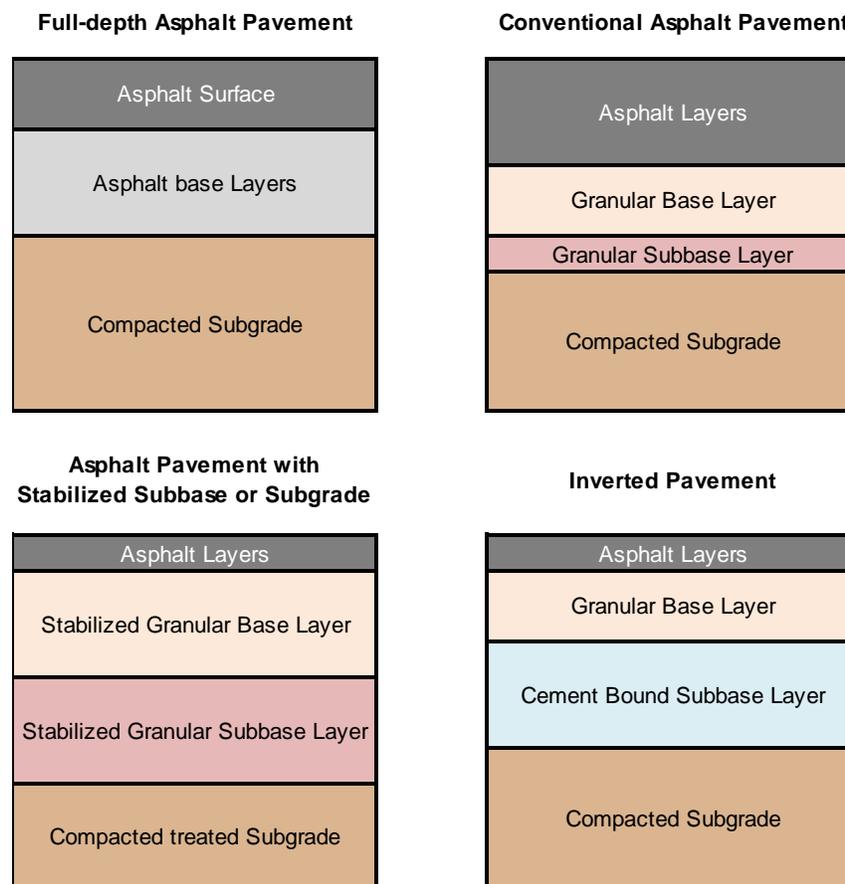


Figure 4-3. Cross sections of various asphalt pavement types (not to scale).

In some cases, granular layers may be used between the asphalt stabilized surface layers and a cement-stabilized subbase, a design referred to as an “inverted” pavement. The “inverted” nature of the design provides strong structural support for the pavement while eliminating the reflection of shrinkage cracks in the cement-stabilized subbase into the asphalt layers. A typical rehabilitation for asphalt pavements is the placement of a structural asphalt overlay, generally defined as having a thickness greater than 2 inches (51 mm). When the slabs in concrete pavements are “rubblized” and then paved with an asphalt overlay, the rubblized concrete effectively serves as an aggregate base.

A detailed description of the various materials used in asphalt pavements are discussed in chapter 3. In general, opportunities for using recycled materials exist in all layers of an asphalt pavement, including the use of RCA and RAP in the granular layers and rubber, RAP, and RAS in the asphalt-stabilized layers. Furthermore, asphalt concrete technology can be used to batch and construct the various asphalt layers. Effective compaction of all pavement layers is critical for improving the performance of all asphalt and granular layers as well as the subgrade, and achievable compaction specifications that maximize overall compaction and minimize the variability of compacted density will improve pavement performance without imposing any significant environmental impact from construction.

Open-graded drainage layers below the asphalt layers may be considered to help handle stormwater. Care must be taken to ensure that drainage layers below the surface have adequate cross-slope and will be maintained to provide free drainage for the life of the pavement and future rehabilitations. This includes providing filters to keep these layers from becoming

clogged, and maintaining free flow from these layers away from the pavement either through “daylighting” to the shoulder or by maintaining shoulder drains.

Various types of interlayers may be considered to improve the performance of granular layers by providing confinement and tensile stress handling capability. Interlayers are designed to allow water to pass through but filter out soil particles, thereby preventing fine subgrade materials from moving into and contaminating granular base, subbase, and drainage layers under hydraulic pressures caused by traffic loadings.

Reconstruction of asphalt pavements consists of removing some or all of the existing structural layers and replacing them, substantially constructing a new pavement structure. There are often many alternatives for recycling materials removed from the existing structure in the new structure. The decision to reconstruct is based on comparison of rehabilitation alternatives considering the condition of the existing pavement and the overall objectives of the owner/agency for the project.

### ***Asphalt Pavement Surface Types***

Asphalt pavement surface layers may be selected to achieve certain functional and structural objectives. Examples of asphalt surface types are:

- Dense-graded asphalt concrete.
- High-friction materials (such as chip seals and microsurfacing).
- SMA for noise, durability, and friction.
- Open-graded asphalt courses for noise, splash/spray, and friction.

In addition to noise benefits, thin open-graded asphalt surfaces transmit stormwater below the surface of the permeable pavement laterally to the shoulder of the road where it is discharged. This causes a slowing of the rate of runoff, which reduces the peak flow of stormwater discharge and also results in pollutants being captured in the open-graded layer (Grant et al. 2003). All these surface layer types can include options for recycling. Additional details regarding tire-pavement noise and various asphalt surface types are provided in chapter 6.

For asphalt overlays, rubberized (using recycled tires) or polymer-modified overlays will often provide improved resistance to bottom-up reflection of existing cracking and top-down cracking. Stress absorbing membrane interlayers of various types are also sometimes used to slow reflection cracking.

### **Open Graded Asphalt Surfaces**

*Open-graded asphalt surfaces are thin asphalt concrete layers (typically 0.5 to 2 inches [13 to 51 mm]) that are constructed with an air void content in the range of 15 to 25 percent of the total mixture volume. The porosity of the surface layer provides a number of potential benefits, including:*

- *High surface friction.*
- *Reduced hydroplaning potential.*
- *Reduction in and splash and spray.*
- *Improved visibility.*
- *Reduced noise levels.*
- *Reduction in urban heat island effects.*

*These benefits are highly dependent on mix characteristics of the asphalt layer, traffic levels (including the use of studded tires), climatic factors, and maintenance.*

*Various options exist for open-graded asphalt mix design to obtain these benefits for the longest period possible, while balancing performance with cost and environmental impact. Open-graded asphalt surfaces may be incorporated into a fully permeable pavement system, as discussed in chapter 6.*

### Asphalt Pavement Rehabilitation Options

Structural rehabilitation strategies for asphalt-surfaced pavements include asphalt and concrete (bonded and unbonded) overlays, both of which provide additional load-carrying capacity to the existing pavement. Schematic cross sections of these various overlay types are provided in figure 4-4. Non-structural overlays, either asphalt or concrete overlays of thickness less than about 2 inches (51 mm), do not add significant structural load-carrying capacity and would be used to address functional pavement issues. Those non-structural overlays are discussed in more detail in chapter 7 (preservation and maintenance).

#### Overlays for Asphalt-Surfaced Pavements

- ✓ **Structural asphalt overlays:** Thicker, new dense-graded asphalt layers placed on existing surface to improve structural capacity.
- ✓ **Structural concrete overlays:** Bonded overlays rely significantly on the thickness and stiffness of the existing asphalt pavement in the structural design whereas in an unbonded overlay the existing asphalt pavement functions as a base layer.

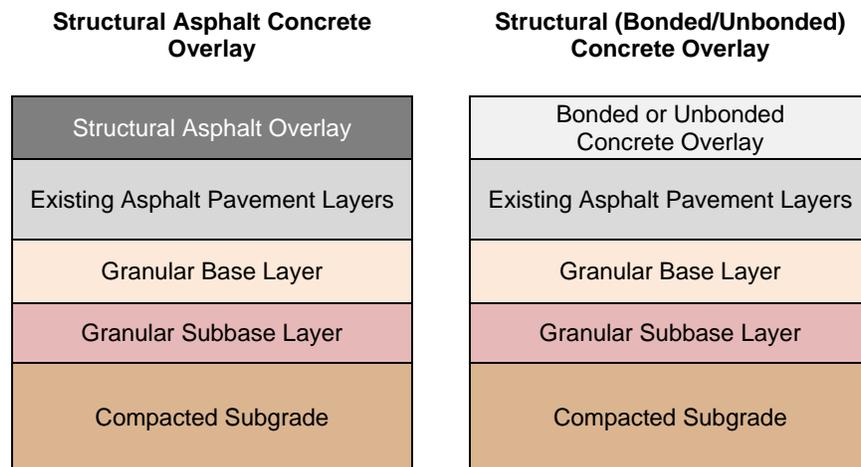


Figure 4-4. Cross sections of rehabilitated asphalt pavement structures (not to scale).

Structural asphalt overlays consist of placement of thicker new asphalt layers (typically more than 2 inches [51 mm]) on the existing surface to increase or restore the pavement's structural capacity as well as improve functional characteristics. Structural asphalt overlays commonly use conventional dense-graded asphalt concrete. For a structural asphalt overlay of an existing asphalt pavement, some or all of the existing asphalt surface layers may be milled in order to improve bonding to the existing surface, eliminate surface rutting, establish the desired surface elevation, and for removal of top-down cracking, old sealants, patching material, and oxidized asphalt materials. These millings are a source of RAP, and could be recycled into the same project or stockpiled for future use.

An alternative to milling is to recycle in place the upper 2 to 4 inches (51 to 102 mm) of the existing asphalt layers with either cold in-place recycling followed by an overlay or with hot in-place recycling (see chapter 7). However, full-depth reclamation (see chapter 8), with no stabilization or stabilized with cement, cement/foamed asphalt, asphalt emulsions or other stabilizers, may be a better selection if all of the existing asphalt layers are heavily cracked, if there is significant delamination between asphalt layers, if the asphalt layers have moisture

damage at various depths, or if there are unbound base layers that will provide inadequate structural support to the asphalt layers.

Structural concrete overlays over existing asphalt surfaced pavements are classified as either unbonded or bonded based on the interface condition between the existing asphalt pavement and the new concrete overlay (Harrington 2008; Harrington and Fick 2014; Torres et al. 2012). Unbonded concrete overlays are placed over existing asphalt, composite, or semi-rigid pavement, with the existing pavement essentially functioning as the base and subbase layers. The unbonded concrete overlay (of thickness 7 to 10 inches [178 to 254 mm]) is typically designed as a new concrete pavement, either a JPCP or as a CRCP, with the existing asphalt pavement acting as a base. If the existing asphalt surface is highly distressed, a thin asphalt interlayer (typically less than 2 inches [51 mm]) may be placed on top to provide a smooth and durable layer beneath the concrete overlay. Part of an existing asphalt surface may also be milled and removed prior to placing the concrete overlay for the same reasons as for structural asphalt overlays on asphalt pavement.

Bonded concrete overlays of asphalt pavement consist of placement of a 3 to 6 inches (76 to 152 mm) thick layer of concrete bonded to an existing asphalt or semi-rigid pavement. The existing asphalt or semi-rigid pavement structure has a larger impact on the design of bonded concrete overlays and thus must be in relatively good structural condition. Slab sizes are much shorter, typically 4 to 6 ft (1.2 to 1.8 m), compared with unbonded concrete overlays that commonly (but not always) have more conventional joint spacing (typically about 15 ft [4.6 m]).

### Concrete Pavement Types

#### *New or Reconstructed Concrete Pavement Structures*

Concrete pavements are constructed or reconstructed with a concrete surface layer resting on a base and possibly a subbase layer, depending on the traffic, climate, and foundation support conditions. As described previously, JPCP and CRCP designs are the most common types of concrete pavements, with typical cross sections of each depicted in figure 4-5.

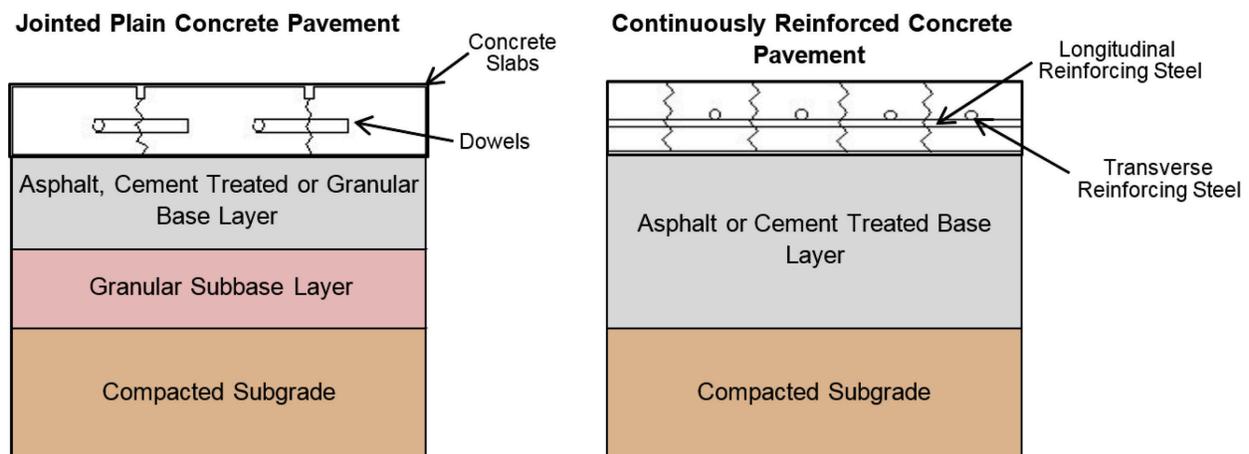


Figure 4-5. Cross sections of concrete pavement structure types (not to scale).

Noted characteristics of JPCP and CRCP designs are as follows:

- JPCP has transverse joints spaced typically about 15 ft (4.6 m) apart and contains no reinforcing steel distributed throughout the slab. Steel dowel bars across transverse joints provide effective load transfer at the transverse joints and significantly reduce joint faulting, pumping, and corner breaks, while JPCP without dowels will tend to have reduced load transfer when slabs contract under colder temperatures. Steel tie bars across longitudinal contraction and construction joints keep these joints tight and in alignment.
- CRCP has no regularly spaced transverse joints but typically contains 0.6 to 0.8 percent longitudinal steel reinforcement (expressed as a percentage of the cross-sectional area of the slab). The higher steel content both influences the development of transverse cracks within a desired spacing (about 3 to 6 ft [0.9 to 1.8 m]) and serves to hold them tightly together. Transverse reinforcing steel may also be used, primarily to support the longitudinal steel.

These traditional concrete pavement sections include opportunities for use of recycled materials in the base and subbase layers as well as various recycled materials in the concrete surface as described in chapter 3.

As with asphalt pavements, reconstruction of concrete pavements consists of removing some or all of the existing structural layers and replacing them with a substantially new pavement structure. There are often many alternatives for recycling materials removed from the existing structure in the new structure. Once again, the decision to reconstruct is based on comparison of rehabilitation alternatives considering the condition of the existing pavement and the overall objective of the owner/agency for the project.

### **Concrete Pavement Surface Options**

Concrete pavements have a number of surface textures that can be constructed to provide different functionality for friction and noise. Transverse tining has commonly been used to provide surface friction, but has been found to be a noisier surface (Rasmussen et al. 2008).

#### **Concrete Pavement Thermal Characteristics**

*Most materials expand when they are heated and contract when cooled. The degree to which this occurs is measured by the coefficient of thermal expansion (CTE), which is presented in terms of the change in unit length of a material as a function of an associated change in temperature. This behavior is important for concrete pavement design, as higher CTE values result in higher stress development due to temperature differences that exist between the top and bottom of the concrete slab. These temperature differences are affected by the albedo (solar reflectivity) of the surface and the conductivity and heat capacity of the concrete and other pavement layers.*

*CTE is a direct user input in the AASHTOWare Pavement ME Design procedure for concrete pavements. Higher CTE values result in higher predicted levels of slab cracking and joint faulting for JPCP (Hall and Tayabji 2011), and a greater incidence of punchouts and associated roughness on CRCP (Roesler and Hiller 2013).*

*The CTE of concrete depends primarily on the coarse aggregate used in the mixture. CTE values can range from around  $4 \times 10^{-6}$  in/in<sup>o</sup>F ( $7 \times 10^{-6}$  mm/mm<sup>o</sup>C) for concrete containing limestone aggregate to a value of about  $6.6 \times 10^{-6}$  in/in<sup>o</sup>F ( $11 \times 10^{-6}$  mm/mm<sup>o</sup>C) for concrete containing quartz aggregate.*

*Given the importance of the CTE in new ME design procedures, many highway agencies are working to characterize the CTE properties of their concrete mixtures. A test protocol for CTE testing has been standardized by AASHTO under T 336 (Hall and Tayabji 2011).*

Other surface textures include longitudinal tining, diamond ground, diamond grooved, and various turf drags. Joint design and construction can also affect noise levels. More information on these surface textures is provided in chapter 5, and information on noise studies related to concrete pavement surface textures is provided in chapter 6.

### *Concrete Pavement Rehabilitation Options*

Rehabilitation strategies for concrete surfaced pavements include structural asphalt overlays and structural bonded and unbonded concrete overlays (non-structural asphalt overlays are considered in chapter 7). Concrete overlays of existing concrete pavements are either unbonded or bonded (Harrington 2008; Harrington and Fick 2014; Torres et al. 2012). An unbonded concrete overlay utilizes a separation layer between the concrete pavement and the new concrete overlay (Smith, Yu, and Peshkin 2002). This has typically been a 1 to 2 inches [25 to 51 mm] thick asphalt material, although some agencies are now using non-woven geotextile materials as a separator layer (Harrington and Fick 2014). This separation layer is placed to ensure independent behavior between the two slabs, thereby minimizing the potential for reflection cracking. Unbonded concrete overlays are typically constructed between about 6 to 12 inches (152 to 305 mm) thick, with the structural requirements based on support conditions and projected traffic loadings. Unbonded concrete overlays are used when the existing pavement deterioration is so advanced that it cannot be effectively corrected prior to overlaying. Figure 4-6 shows the cross sections of rehabilitated concrete pavement structures.

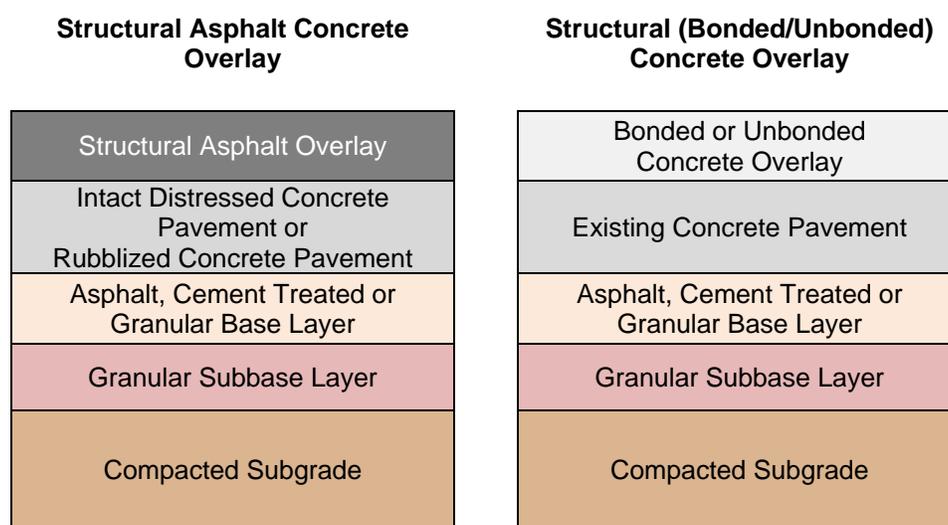


Figure 4-6. Cross sections of rehabilitated concrete pavement structures (not to scale).

Bonded concrete overlays consist of a thin layer of concrete (typically 3 to 4 inches [76 to 102 mm] thick) that is bonded to the existing concrete pavement (Smith, Yu, and Peshkin 2002). These are used to increase the structural capacity of an existing concrete pavement or to improve its overall ride quality. A critical construction and performance aspect of bonded concrete overlays is the achievement of an effective bond between the overlay and the existing concrete pavement in order to create a monolithic pavement system. Bonded concrete overlays of existing concrete pavement are not used frequently and require the existing pavement to be in good to excellent structural condition prior to placement (Harrington 2008; Harrington and Fick 2014).

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

#### **Overlays for Concrete-Surfaced Pavements:**

- ✓ **Structural asphalt overlays:** Overlay is placed on intact, distressed concrete using tack coat; if existing concrete is in poor condition, then crack and seat or rubblization procedures may be used.
- ✓ **Structural concrete overlays:** Bonded or unbonded. Unbonded overlays contain an interlayer between the existing and new concrete to provide separation; bonded overlays consist of a thin, concrete layer bonded to existing concrete pavement to produce a monolithic structure.

### *Composite Pavement Types*

#### ***Asphalt-Surfaced Composite Pavement***

Asphalt-surfaced composite pavements refer to asphalt layers placed on a concrete pavement, either as part of new pavement construction or as part of a rehabilitation project. This type of design takes advantage of both paving material types, and may be used for a number of reasons, including reduced noise, increased friction, improved smoothness and rideability, and utilization of higher volumes of recycled materials in the concrete layer (if part of a new pavement construction). A thin asphalt layer with low noise emissions and high frictional properties can be placed over a durable and fatigue resistant concrete layer to achieve a quiet, safe, and potentially long-lasting structure. The asphalt layer may also help reduce negative temperature gradients (cold on top), reducing excessive tensile stresses that can lead to cracking (Rao et al. 2013a; Rao et al. 2013b). A typical cross section of an asphalt-surfaced composite pavement is shown in figure 4-7.

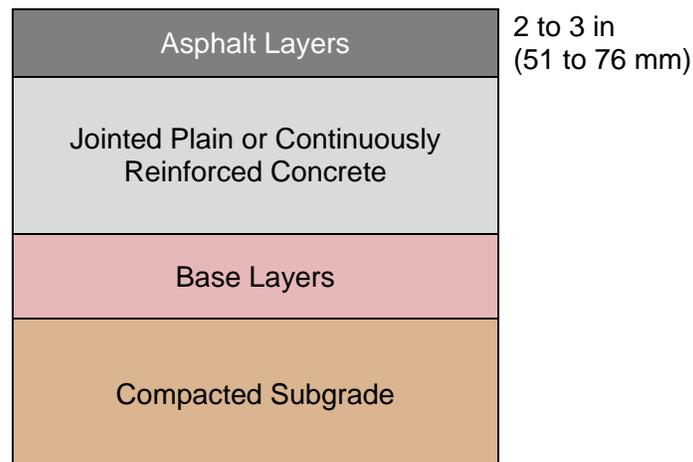


Figure 4-7. Cross section of asphalt-surfaced composite pavement.

### *Two-Lift Composite Concrete*

Another type of composite pavement is constructed using two independent lifts of concrete that are placed “wet on wet” so that an effective bond develops between them. The properties of the two layers are designed for the specific application. The upper lift may consist of abrasion resistant and more durable materials optimized for surface characteristics such as noise and texture while the lower lift utilizes recycled materials or aggregates of lesser quality (Darter 1992; Hall et al. 2007; Van Dam et al. 2012; Rao et al. 2013b). This optimized approach serves to not only lower costs, but also reduces environmental impacts as well. A typical cross section of a two-lift concrete pavement is shown in figure 4-8.

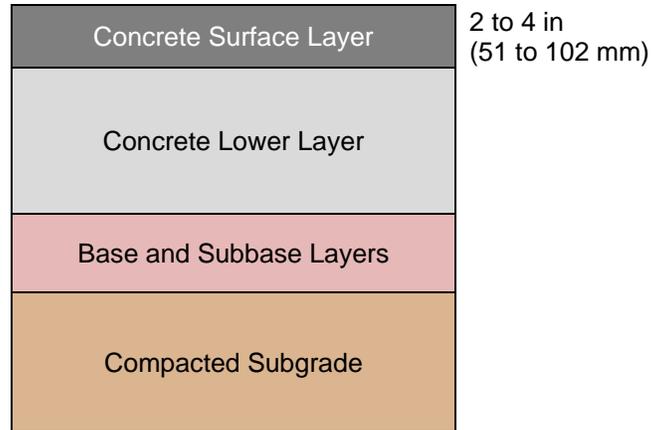


Figure 4-8. Cross section of two-lift concrete pavement.

Over the years, a number of projects featuring two-lift concrete have been constructed (Sommer 1994; Smiley 1995; Wojakowski 1998; NCPTC 2008; Tompkins, Khazanovich, and Darter 2010; Brand et al. 2012). Two recent examples of two-lift concrete pavements include:

- A composite pavement constructed by the Missouri DOT in 2011 consisted of an 8-in (203-mm) bottom lift of conventional concrete and a top lift of 2 inches (51 mm) of concrete containing photocatalytic cement on Route 141 in St. Louis County (Cackler et al. 2012; Sikkema 2013).
- A composite pavement on the I-88 Illinois Tollway consisted of an 8-in (203-mm) ternary concrete bottom lift containing 20 percent fractionated coarse RAP and a 3.5-in (89-mm) top lift of conventional concrete pavement materials (Brand and Roesler 2013).

### *Semi-Rigid Pavement*

Semi-rigid composite pavements are composed of an asphalt surface course placed on a cementitious layer (e.g., CTB, LCB, or RCC). Semi-rigid pavements are often used where high-quality aggregate is not readily available. However, the reflection of shrinkage cracks from the cementitious layer into the asphalt surface may need to be addressed. One approach to minimize reflection cracking is to “microcrack” the cementitious layer with impact rollers as it is curing, which produces well-distributed, fine cracks that exhibit little movement (Sebesta 2004). Another approach is to saw narrow joints in the cementitious layer to more uniformly distribute crack movements and thereby slow the rate of reflection cracking. A final way to establish a tight cracking pattern is to introduce discrete cracks with an impact device (Cockerell 2007).

There are a number of potential opportunities for using large quantities of recycled materials in semi-rigid pavements. For example, the cementitious base layers can be produced either using plant-mixed materials, or through full-depth reclamation with cement stabilization (as described in chapter 8). A typical cross section of a semi-rigid pavement is shown in figure 4-9.

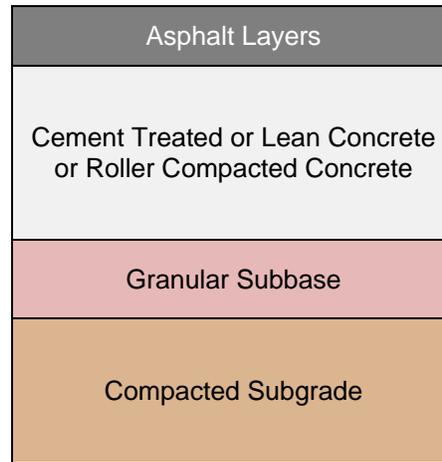


Figure 4-9. Cross section of semi-rigid pavement.

### *Rehabilitation of Composite Pavement*

Rehabilitation alternatives for composite pavement types are the same as for other types of asphalt- and concrete-surfaced pavement.

### *Modular Pavement Systems*

Modular pavement systems are composed of a wide variety of precast components in order to either rapidly construct or repair a section of roadway or to provide an aesthetically pleasing design. One type of modular pavement is precast concrete slabs, of which a number of different technologies have become available over the past 15 years (Tayabji, Ye, and Buch 2012). They are typically used for very short construction windows to minimize user delays and to provide better performance than might be obtained using rapid-setting concrete materials with cast-in-place construction. Better performance is expected because the precast concrete is cast and cured under controlled conditions, and is therefore not exposed to potentially poor field curing conditions and trafficking while curing. In addition, effective joint load transfer can be built into the slab either through unique doweling configurations or, for some systems, through post-tensioning (Merritt, McCullough and Burns 2003; Smith 2008; Smith 2012). Grinding is performed after some installations to improve smoothness.

#### **Modular Pavement System Types**

***Intermittent Systems:*** These are isolated pavement repairs conducted using precast concrete slabs and typically include full-depth repairs of deteriorated joints and cracks and full-panel replacement of severely deteriorated slabs. Several different systems are available, with successful installations in New York, New Jersey, and Michigan, among others locations.

***Continuous Systems:*** These involve full-scale rehabilitation of asphalt and concrete pavements. Common systems that have been used in the U.S. include jointed precast concrete pavement systems with dowel bars and precast, prestressed concrete pavement systems formed by post-tensioning together a series of panels. These continuous systems have been constructed in a number of states, including California, Delaware, Texas, Missouri, New Jersey, New York, and Virginia.

Another example of a modular pavement system is interlocking concrete pavements. These are often used on low speed facilities or in urban areas to provide aesthetically pleasing roadways (ASCE 2010; Smith 2011).

Modular pavements potentially permit thinner and longer lasting structures that could reduce environmental impacts over the life cycle. Modular pavement systems also allow easy access for utility cut repairs to reduce repair costs and minimize user delays.

### *Pavements and Stormwater Management*

Pavements can be constructed using permeable materials to innovatively control, manage, and treat stormwater runoff. Permeable pavements can capture and store stormwater runoff, allowing it to percolate into the ground and thereby recharge groundwater supplies while also controlling outflow. Fully permeable pavements, shown in figure 4-10, are defined as those in which all layers are intended to be permeable and the pavement structure serves as a reservoir to store water during storm periods in order to minimize the adverse effects of stormwater runoff.

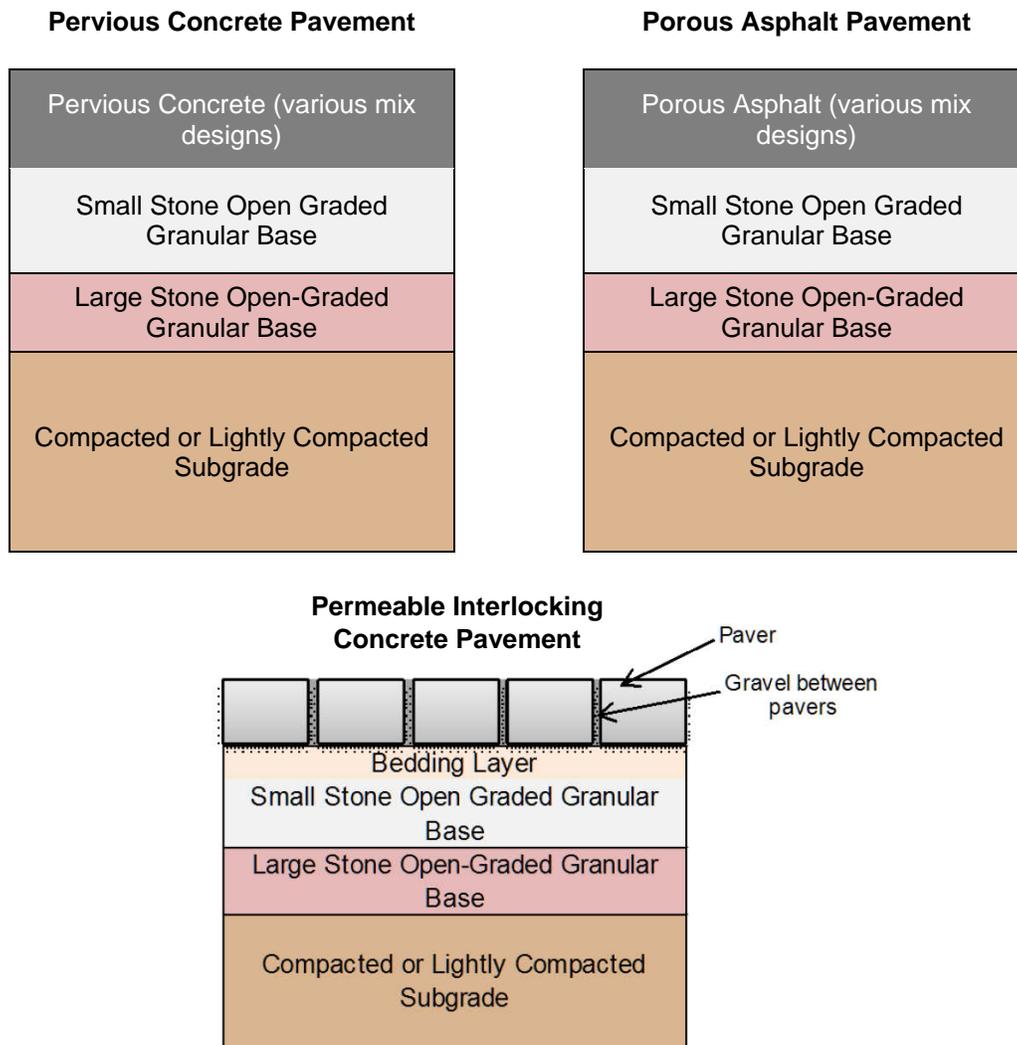


Figure 4-10. Cross sections of pervious concrete pavement, porous asphalt pavement, and permeable interlocking concrete pavement.

Most applications of fully permeable pavements in North America have not been subjected to high-speed traffic or heavy trucks, which reflects concerns about durability. Structural design methods are empirical in nature, and are available from the National Asphalt Pavement Association (Hansen 2008), the American Concrete Pavement Association (ACPA 2009), and the Interlocking Concrete Pavement Institute (Smith 2011) for design of porous asphalt, pervious concrete pavements, and permeable interlocking concrete pavements, respectively.

For state highway agencies, fully permeable pavements are being considered as a shoulder retrofit adjacent to conventional impermeable pavement with geofabric barriers to limit water affecting the layers in the impermeable pavement, and for some low-speed applications carrying trucks. An ME design approach and a preliminary LCCA have been produced for fully permeable pavements to carry trucks (considering both structural and hydraulic capacity) for California conditions (Jones et al. 2010; Li, Jones, and Harvey 2012a; Li, Jones, and Harvey 2012b). More information regarding fully permeable pavements is included in chapter 6.

### Layer and Material Type Selection

The pavement type alternative determines what layer combinations and materials (virgin, recycled, or co-product) can be used. For the type of facilities considered here, all pavement types will have a permanent surface layer (asphalt or concrete), a higher quality base layer that may or may not be stabilized, and perhaps even a subbase layer to provide for added subgrade protection from moisture, frost, and repeated traffic loading. Base and subbase material properties and combinations are chosen for multiple reasons including transmitting and spreading the load-induced stresses to the subgrade, providing uniformity of support to the surface layer, providing subsurface drainage, protecting lower layers from frost penetration, and providing a working platform for surface course construction. Base and subbase material layers can often make use of more recycled and lower quality aggregates to reduce construction costs and emissions while still achieving the structural goals of the layer. To improve pavement performance and potentially reduce the thickness of the surface layer, these layers can be stabilized if desired. Trade-offs between the impacts of reduced surface layer thicknesses versus the impacts of foundation layers stabilization can be considered with LCA (see chapter 10), as can trade-offs between the impacts of increased thickness versus materials of lower quality but with reduced environmental impact.

Subgrades should always be compacted to improve stiffness and shear strength and to reduce permeability. Subgrades may also be treated or stabilized to further improve stiffness and shear strength. The improvement of these properties may permit thinner pavement structures above the subgrade to carry the same traffic. Treatment and stabilization materials can include cement, lime, asphalt emulsions, fly ash, kiln dust, or other cementitious materials. Guidance on stabilization selection, mixture design, and construction are available from the FHWA (Carpenter et al. 1992a; Carpenter et al. 1992b). These two volumes represent the revisions to original manuals prepared in 1980 (Terrel et al. 1980).

Clay subgrades may also be treated with lime to reduce plasticity and improve compaction, although care must be taken to check that a given subgrade soil will not be susceptible to swelling due to unwanted chemical reactions, such as certain expansive lime-clay reactions (Mitchell 1986). Trade-offs between the impacts of reduced surface layer thicknesses versus the impacts of subgrade stabilization can be considered with LCA (see chapter 10).

Chapter 3 provides an overview of the various virgin, recycled, co-product, and waste materials that are currently being used in pavements. The availability of recycled (e.g., RCA, RAP, RAS, rubber) and co-product (e.g., slag, fly ash, limestone dust) materials must be thoroughly explored as part of the design process since they may have a significant impact on the LCA in terms of cost, energy, and emissions. To effectively, efficiently, and safely use all available resources (virgin, recycled, and co-product materials), existing agency guidelines and specifications should be reviewed or new ones created to ensure the selected pavement sustainability strategies will provide the desired pavement performance.

One potential strategy for reducing the energy, emissions, and overall environmental impact of transporting pavement materials (see chapter 3 for details of minimizing material transportation) is to reduce the cross section of the new pavement or rehabilitation structure by using higher quality materials or by balancing the use of locally available materials with higher quality materials in critical pavement layer locations. ME design procedures, with appropriate material characterization, can be used to identify the required change in the cross section to ensure that performance requirements are still met even when sub-optimal recycled or local materials are employed.

As described in chapters 3, and 5, the main contributors to energy consumption, GHG emissions, and other environmental impacts in the paving materials production phase are cement, asphalt binder, and aggregate production, and the asphalt and concrete mixing plant operations. The production of polymers, crumb rubber, and other additives in asphalt mixtures and chemical admixtures for concrete pavements can potentially improve pavement performance or permit thinner structures, but may also result in increased energy and emissions. A full LCA analysis will assist in the selection of materials for use in the design (see chapter 3).

Consideration of energy dissipation due to structural responsiveness is an area of current research and validation, and contributions to energy use and GHG emissions may be a consideration in the structural design (see chapter 6).

### Drainage

Poor drainage conditions can contribute to early failures and reduced pavement life, and therefore can significantly increase the environmental and cost impacts of the original pavement because of early and more frequent maintenance and rehabilitation activities. It is essential that the need for drainage be reviewed for all new and rehabilitation projects. Failing to remediate poor drainage, even where it affects a relatively small percentage of the project length, will lead to increased life cycle costs and higher environmental impacts.

### Construction Quality Specifications

The sustainability of a pavement structure can be improved through any increases in pavement performance (e.g., longer service life, higher and maintained levels of smoothness and frictional properties). In many cases, this can be achieved with small increases in construction quality and concomitant reductions in overall variability. Because the development of effective construction quality specifications is part of the design process, a careful review of construction specifications is appropriate to see where increased levels of quality could be achieved and impact performance. Moreover, the implementation of an effective quality assurance plan promotes higher levels of quality should be part of the effort to improve pavement sustainability through design. More details regarding construction quality are presented in chapter 5.

### *Material Trade-Offs*

As has been discussed previously, there are a number of trade-offs that can be evaluated regarding the use of materials in a pavement design; for example, trade-offs between the desirable characteristics of a material and the distance from which it must be transported, or trade-offs in the thickness requirements of the material for it to perform adequately versus the benefits of treating or stabilizing the material to reduce thickness. Materials specifications should be reviewed to determine whether they impose any restrictions on using materials that have lower life-cycle environmental impact but produce the same performance when used in a given structure. In some cases, the use of thicker layers of less desirable recycled or local material may still provide acceptable performance but with lower economic and environmental impacts.

It may be that some outdated specifications require virgin materials because the technology for effectively using recycled materials was not fully developed at the time the specifications were written. The use of empirical design methods requires that performance be observed for sufficient time to assess the risk of failure, which for many materials requires years of monitoring before being considered acceptable for inclusion in routine designs. In other cases, there may be an assumption that virgin materials inherently possess superior properties compared with recycled materials. The more widespread use of ME design methods should speed the implementation of new and innovative materials through effective laboratory characterization.

### *Compaction*

As described in chapter 5, more stringent compaction specifications for subgrade, unbound granular, cement-treated, and asphalt materials can result in increased pavement life. Increased levels of compaction improve the density, stiffness, and strength of unbound and cement-treated materials, and increase the stiffness, durability, rutting, and fatigue performance of asphalt-bound materials. Many agencies use a standard specification of 90 to 95 percent of standard AASHTO T 99 compaction for subgrades and granular materials. Increasing compaction to 95 to 100 percent for granular materials will result in increased pavement life with the increase in environmental impact primarily coming from the increased use of construction equipment. Airfield pavements use 100 percent of modified AASHTO compaction (AASHTO T 180) for aggregate bases with similar gradations to those used for highways. The use of 95 percent of standard AASHTO T 99 compaction for subgrades instead of 90 percent, or even 95 percent, of modified AASHTO T 180 compaction should improve pavement performance with minimal environmental impact. The primary trade-offs are increases in construction cost, potentially an extension to the construction schedule, increased quality assurance testing by the owner/agency for verification, and potentially some increase in construction equipment emissions. However, increases in pavement life and extension of the time that the pavement is smooth will often have a much larger positive impact than the additional equipment emissions required to achieve those higher levels of compaction. Verification testing should be performed to ensure that more stringent compaction specifications can be achieved for the given material. An example is given in chapter 5 regarding the benefits of increased life from improved asphalt compaction.

### *Smoothness*

Obtaining good initial smoothness levels during construction of new or rehabilitated high traffic volume roadways, and designing the pavement to maintain those levels of smoothness throughout its life, can result in a large reduction of use-phase energy/emissions compared to impacts associated with materials production and construction. However, the impacts associated with the materials production and construction phases will likely be more important for lower

volume routes (see chapter 6). Smoothness acceptance levels should be part of the construction specifications developed for the design (preferably in terms of IRI), with high-volume traffic facilities deriving greater benefits from higher levels of initial smoothness.

### Construction Process and Traffic Management

One sustainability aspect that can be considered during the pavement design and construction process is the integration of traffic management plans in order to adequately consider and possibly minimize user delays. For example, more rapid means of pavement construction or rehabilitation can help reduce user delays. Construction analysis programs for pavements, such as CA4PRS (Lee, Harvey, and Samadian 2005; Lee and Sivaneswaran 2007; Lee et al. 2009; FHWA 2008; Caltrans 2013), can be used to analyze the effects of pavement design on traffic delays and construction window policies. The impact of traffic delays on vehicle GHG emissions and energy consumption relative to the impacts of materials production, construction, and the use phase will depend on the types of delay and the number and types of vehicles affected. It is possible that traffic slowing in a construction zone could conceivably have a beneficial effect on sustainability; for example, if traffic speed in a work zone is reduced from 65 mi/hr (104 km/hr) to 45 mi/hr (72 km/hr), the overall vehicle fuel economy is expected to improve.

### Consideration of Future Maintenance and Rehabilitation

The design of new pavements and rehabilitation projects should include consideration of future maintenance and rehabilitation that will be required based on the design decisions. These future decisions should include consideration of maintaining the overall structural capacity of the pavements, its overall functional capabilities (e.g., smoothness, friction), and future roadway recycling and reuse (see chapter 8 on end-of-life strategies).

## **Sample Sustainable Design Strategies**

### Longer Life Pavement

Longer life pavements can be achieved as a policy objective in new, rehabilitated, and reconstructed pavements and are generally justified for higher volume facilities. Design lives may range from 30 to more than 60 years and can be accomplished using both asphalt and concrete designs. Longer life design options should be considered for new corridors and rehabilitation of existing pavements that are severely distressed and may also possess geometric deficiencies, and may afford the opportunity to reduce life-cycle costs, user delays, and environmental impacts as compared to a standard, 20-year pavement design.

A general rule for load-related cracking is that as critical tensile strains or stresses decrease (for either concrete or asphalt pavements), the overall structural capacity of the pavement (i.e., the number of truck loads it can carry) increases logarithmically. Therefore, when there are heavy volumes of traffic, higher structural capacity can be achieved by increasing the bending resistance of the pavement; this can be accomplished by increasing the thickness or by increasing the material stiffness (or both). Longer life designs can select innovative combinations of layer thicknesses and materials to achieve this, including the use of recycled materials in the lower layers. However, effective material and construction specifications are essential in order to reduce variability and maximize the performance of the selected materials. Because of the increased thicknesses or increased material stiffnesses, longer life designs may increase initial costs and possibly initial environmental impacts, but the overall life-cycle costs and environmental impacts over the life cycle are expected to be less.

### *Longer Life Asphalt Pavement*

Longer life asphalt pavement designs can be developed to provide a number of sustainability benefits, including:

- Reduction in the amount of asphalt mixture through the selection of materials and construction requirements for better compaction that produce greater bending resistance than conventional materials; this reduces the cross-sectional area compared with what would be required with conventionally designed and compacted asphalt mixtures.
- Incorporation of higher quantities of RAP combined with stiffer and less viscoelastic asphalt binders in the middle layer; this reduces the amount of new asphalt binder used (and its commensurate environmental burden) and provides increased stiffness and reduced viscoelastic energy dissipation.
- Use of modified open-graded surfaces to reduce noise, slow stormwater runoff, and trap pollutants, and provide a sacrificial layer for top-down cracking.
- Use of recycled concrete pavement or building waste as the granular base layer.

If the longer life pavement is designed so that the tensile strain at the bottom of the asphalt layers is below the limit at which the potential for cracking begins, it is often referred to as a perpetual pavement (see figure 4-11). The composition of each of the layers in a perpetual pavement is described below (starting from the bottom of the pavement system and working to the surface):

- A fatigue-resistant bottom layer is provided that resists damage under tensile strains caused by traffic, and thus stops cracks from forming in the bottom of the pavement. This bottom-up fatigue cracking resistance can come from increasing the total pavement thickness such that the tensile strain at the bottom of the base layer is insignificant (which requires more asphalt), or by specifying air voids to between 0 and 3 percent and slightly increasing the asphalt content to achieve this high level of compaction (referred to as a “rich-bottom” layer).
- The next layer is designed specifically to increase the bending stiffness through the use of stiffer conventional asphalt and potentially higher RAP contents. This layer can also have an increased compaction requirement to increase the stiffness and fatigue resistance of the section.
- The third layer from the bottom is designed specifically to resist surface-initiated distresses such as top-down cracking, rutting, and low-temperature cracking (where applicable). Some typical mixtures used for the surface layer are polymer-modified asphalt concrete and SMA. ME pavement design procedures can be used to design the structure considering the different pavement materials (Timm and Newcomb 2006; Buncher and Newcomb 2000; Newcomb, Willis, and Timm 2010; Harm 2001).
- A fourth layer—typically either a high-quality polymer- or rubber-modified, open-graded or gap-graded mixture or a 1 to 2 inches (25 to 51 mm) SMA—can be placed on top of the rut resistant layer and is designed for abrasion resistance and vehicle safety. This layer is considered to be a sacrificial layer in a 30- to 50-year long-life asphalt pavement. Once its effectiveness is diminished (approximately every 10 to 15 years), it can be removed, recycled, and replaced. Many open-graded and SMA mixtures used for this layer can provide tire-pavement noise reductions when compared to dense graded materials (Rezaie, Harvey, and Lu 2012).

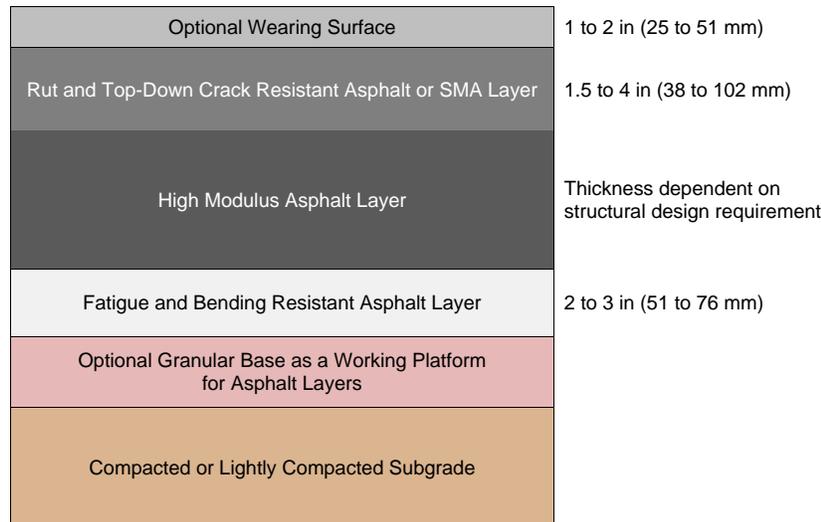


Figure 4-11. Perpetual pavement cross section.

For longer life structural overlays, the prudent use of polymer-modified asphalt materials may also be a way to achieve longer life (as compared to conventional materials). Polymer-modified asphalt can extend the life of the surface by increasing rutting resistance and decreasing susceptibility to top-down cracking. It can also be used to decrease reflection cracking in an overlay application. The increased life can help decrease the frequency of maintenance and rehabilitation, thus reducing some environmental impact. However, polymer modification should be used where its benefits are of most value, because polymer modification may increase overall GHG emissions of the asphalt pavement design due to the manufacture and production of the polymer itself (Bernard, Blomberg, and Southern 2012).

### *Longer Life Concrete Pavement*

Longer life concrete pavements (either JPCP or CRCP), with anywhere from 35- to 60-year design lives, are designed to maintain structural integrity and require only periodic retexturing of the surface to restore smoothness, friction, and noise performance. Longer life concrete pavements are designed to resist the heavy truck traffic that will cause repeated load distresses such as fatigue cracking, faulting, and punchouts. These design objectives are achieved by using durable concrete mixtures, adopting slightly thicker concrete slabs placed on non-erodible bases, including properly designed and corrosion-resistant dowel bars or reinforcing steel, and incorporating stress-relieving design features such as tied concrete shoulders or widened slabs.

Figure 4-12 shows an example of a longer life CRCP designed for fatigue resistance and low maintenance requirements. The life-cycle environmental benefits of the longer life CRCP have to be evaluated using LCA and compared to the environmental impacts associated with the inclusion of the steel reinforcement.

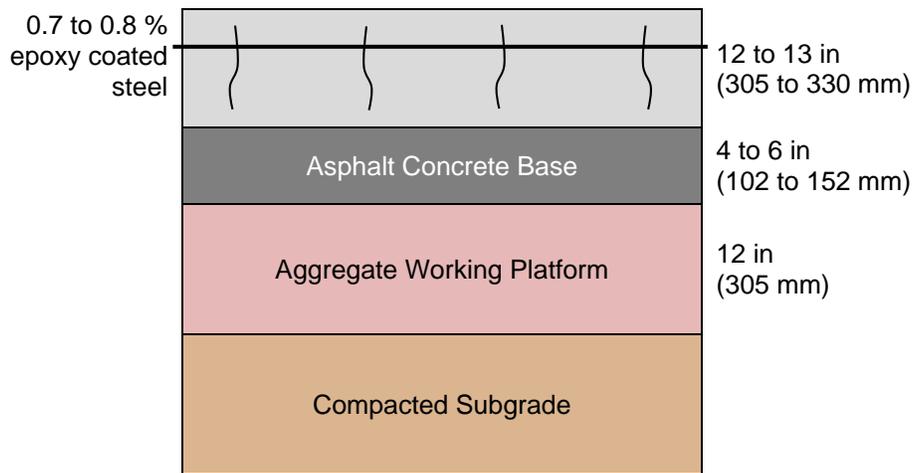


Figure 4-12. Example of CRCP longer life design.

Recycled concrete aggregate can be used in all layers of concrete pavements with the majority of the recycled concrete placed in the granular base or subbase layer to reduce subgrade stresses, protect against frost action, and to enhance subsurface drainage. Recycled concrete or coarse RAP can be used in the concrete mixture as long as the mixture design is adjusted for the expected changes to the fresh and hardened concrete properties (Snyder et al. 1994; Sturtevant 2007; Roesler, Huntley, and Amirkhani 2011; Brand et al. 2012; Brand and Roesler 2013). Co-product materials such as fly ash and slag cement are commonly used in all types of concrete pavements including longer life designs, as these significantly improve the durability of the concrete (see chapter 3 for more information).

### Design for Local Materials or Low Impact Transportation

Designing for the incorporation of local materials to reduce transportation costs should be considered for all aggregate materials, whether they are used in asphalt, concrete, or unbound layers. Minimization of earthwork hauling for the roadway foundation is also another consideration. Alternatives can be analyzed to minimize both costs and environmental impacts.

### Accelerated Construction

Accelerated construction can be employed that minimizes the duration of construction and associated lane closure times. Construction processes and materials such as rapid-setting or high-early-strength concrete, modular concrete, or rubblization/asphalt overlays are examples of accelerated construction. Each of these options will expedite the construction process, thus reducing user delays, reducing emissions, and improving safety (by reducing the risk of crashes).

### Single-Lane Rehabilitation

In many situations involving multi-lane highways, the outer (truck) lanes may be in need of a structural rehabilitation or reconstruction, while the inner lanes are still in relatively good condition. If a thick overlay (concrete or asphalt) is needed on the truck lanes, the inner lanes must receive the same treatment in order to maintain elevations. In these cases, consideration could be given to the reconstruction of the outer lane, with the new pavement structure either matching the surface elevation of the inner lanes, or perhaps slightly higher to accommodate the placement of a thin overlay on the inner lanes to restore functional performance. Computations can be made for the environmental impact of each scenario (complete overlay vs. outer lane reconstruction), including consideration of the recycling of the existing pavement and associated traffic delays.

Local reconstruction of the outer traffic lane can also be considered on corridors with mixed pavement types (i.e., different pavement types in adjacent lanes), provided that this does not impose any major maintenance issues. Existing asphalt pavements can receive either an inlaid reconstructed asphalt or concrete outer lane, and existing concrete pavements can receive new inlaid concrete truck lanes and an asphalt overlay on the passenger lanes that matches the elevation of the outer lanes. There are also opportunities for inlaid reconstruction with semi-rigid pavements in the truck lanes. The pavement materials that are removed can be recycled next to the construction site into the new truck lanes.

### Consideration of Use Phase in Design

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

1. Smoothness over the design life of the pavement. High levels of smoothness maintained throughout the life of the pavement will incur reduced environmental impacts.
2. Overall pavement longevity. This serves to not only decrease the life-cycle costs, but also reduces the environmental and social impacts associated with materials production, construction, and periodic maintenance and rehabilitation.

Which of these factors is most important depends on the context of a particular project. The importance of both depends, in large part, on the traffic volumes using the facility. Where there are heavy traffic volumes, the benefits of smoothness over the design life can be much larger than material production and construction impacts. Conversely, for low-volume roads and highways, material production and construction will often tend to dominate the net calculation of environmental impacts. Additional details on use-phase considerations are discussed in chapter 6.

### **Major Issues and Trade-offs in Designing More Sustainable Pavements**

Based on the discussions presented in this chapter, the major design and policy objectives, associated approaches to providing sustainability improvements, and potential trade-offs with regard to economic, environmental, and societal impacts are summarized in table 4-2.

### **Future Directions and Emerging Technologies**

There are a number of potential future directions and emerging technologies in the pavement design arena that may have a significant effect on improving overall pavement sustainability. These include:

- Improvements in ME design: testing, models, validation. Further improvements in the ability of laboratory testing to characterize materials properties that control performance, and in models that use those properties to predict pavement performance, will permit improved and more rapid consideration of new materials in pavement design. There are a number of accelerated pavement testing (APT) facilities around the world that can be used to provide more rapid feedback on the performance of full-scale constructed pavements to help validate new models, materials, and structures. This should result in a shorter time for their implementation. Balancing the risk versus reward in the use of new materials and structures, incorporating them into new testing and design procedures, and providing training of engineers to use them, are all significant challenges. ME design procedures will need to see more widespread use in order to provide more precise performance estimates with consideration for construction variability.

Table 4-2. Summary of major issues and trade-offs for improving pavement sustainability through design.

<b>Design/Policy Objective</b>	<b>Sustainability Improving Approach</b>	<b>Economic Impact</b>	<b>Environmental Impact</b>	<b>Societal Impact</b>
<b>Achieve Longer Life</b>	Use ME design to be able to consider alternative materials, construction specifications and structures to increase life for same pavement thickness <sup>1,2</sup> . Use selected recycled materials to improve structural characteristics. Require higher construction quality.	Virgin materials may increase cost; increased construction quality may increase cost; reduced frequency of maintenance and postponement of rehabilitation may decrease cost.	Virgin materials may have higher environmental impact during production; decreased maintenance frequency may decrease emissions; increased pavement quality may decrease user emissions.	Stays smoother longer; less delay associated with maintenance.
<b>Achieve Longer Life</b>	Use of higher quality materials.	Increased cost of materials; decreased cost of maintenance.	Potential for increased emissions due to production and transportation of higher quality materials if not locally available; higher quality pavement may result in lower user and maintenance emissions.	Higher quality pavement; less delay associated with maintenance.
<b>Achieve Longer Life</b>	Improved construction specifications (less variability, greater density, stiffness, strength, durability depending on material) <sup>2</sup> .	Somewhat increased initial cost; could decrease maintenance cost or upfront cost if reduced thickness is used.	Less frequent maintenance or reduced thickness will reduce environmental effects of construction and materials use; additional initial construction work may have minor impact.	Less delay associated with decreased maintenance.
<b>Consider Inlaying New Truck Lane Pavements (vs. Multi-lane Overlay)</b>	Minimize total material used for rehabilitation by not overlaying lanes to match grade that do not have structural needs.	Can reduce cost; may cause some additional traffic delay.	May reduce total amount of new materials needed; can consider recycling materials removed from old truck lanes.	May cause more initial traffic delay due to closure for reconstruction.
<b>Obtain Same Life for Reduced Thickness</b>	Use ME design to consider new materials, construction specifications, pavement structure types <sup>1,2</sup> .	Virgin materials may have higher cost; increased construction quality may increase cost.	Potential increase due to production of virgin material; less material use lowers environmental impact due to reduction in production, transportation and construction.	May reduce traffic delay due to more rapid construction.
<b>Reduce Noise Emissions</b>	Use of noise reducing asphalt (open-graded) or concrete (new generation concrete surfaces) surfaces. <sup>3</sup>	Increased cost; more frequent replacement for the asphalt surface.	Minor impact of additional grinding/grooving for concrete; more materials use and construction.	Reduction of noise in surrounding areas.

Table 4-2. Summary of major issues and trade-offs for improving pavement sustainability through design (continued).

<b>Design/Policy Objective</b>	<b>Sustainability Improving Approach</b>	<b>Economic Impact</b>	<b>Environmental Impact</b>	<b>Societal Impact</b>
<b>Achieve/ Maintain Pavement Smoothness</b>	Consider smoothness over the pavement life as a key design parameter, especially for high traffic volume routes. Include construction specifications for smoothness, design features to maintain smoothness, and costing of maintenance to keep surface smooth.	Potential for small to moderate increases in initial costs but reduced life-cycle costs due to longer pavement lives. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use, particularly on high traffic volume routes.	Improved economic efficiency.
<b>Maximize Use of Recycled and Local Materials</b>	Use recycled pavement materials to replace virgin materials and minimize transportation distances for materials. <sup>1</sup>	Higher variability in recycled material quality may increase maintenance frequency and life-cycle cost; generally reduces initial cost.	Reduced impact of materials production and transportation; less use of scarce materials; use of stabilizers have an impact and can be compared with benefits of reduced need for resurfacing layers, transportation of materials, etc.	May increase maintenance delay if materials do not perform as expected in design; reduced landfill disposals.
<b>Maximize Use of Recycled Material</b>	Use recycled materials from other industries to replace virgin materials. <sup>1</sup>	Use where transportation cost feasible if not locally available; Evaluate variability in material quality to avoid increase maintenance and rehabilitation; generally reduces initial cost; additional processing or construction issues may increase initial cost.	Use where transportation and processing are environmentally beneficial; may reduce future recycling if inclusion of recycled materials makes future recycling too costly, unpredictable or difficult; reduced impact of virgin materials production; less use of scarce materials.	May increase maintenance delay if materials do not perform as expected in design; reduced landfill disposals.
<b>Minimize Impact of Utility Construction</b>	Eliminate or minimize utility cuts in pavement, or use pavement systems that allow easy restoration of pavement structure after utility work (utility corridors in pavement).	Higher initial cost; reduced life-cycle costs due to less frequent maintenance and rehabilitation; reduced cost of maintenance and rehabilitation with no manhole covers; reduced life-cycle cost if longer life designs are used.	Potential increased initial materials and construction impacts of utility corridor; reduced impacts due to longer pavement life, less frequent maintenance and rehabilitation. Keeping utilities out of pavement improves ability to do in-place recycling strategies.	Smoother pavement over life cycle; increased pavement life resulting from less frequent repairs and patching. Keeping utilities out of pavement improves ability to do in-place recycling strategies.

Table 4-2. Summary of major issues and trade-offs for improving pavement sustainability through design (continued).

<b>Design/Policy Objective</b>	<b>Sustainability Improving Approach</b>	<b>Economic Impact</b>	<b>Environmental Impact</b>	<b>Societal Impact</b>
<b>Minimize Impact of Construction</b>	Accelerated construction.	Often reduces initial user costs but increases agency costs; must maintain quality standards.	Difficulty with shorter construction may influence quality and functional life; accelerated materials may have a shorter performance life.	Reduced traffic delay.
<b>Use Pavement to Capture Runoff Pollutants and Reduce Hydraulic Requirements from Storms<sup>3</sup></b>	Use partially permeable pavement (e.g., open-graded asphalt).	Increased cost; need for more frequent resurfacing.	Increased environmental impact of materials and construction for open-graded layers; reduced pollutants in water.	Cleaner water for surrounding area.
<b>Use Pavement to Capture Runoff Pollutants and Reduce Hydraulic Requirements from Storms<sup>3</sup></b>	Use fully permeable concrete or asphalt pavement (very little application to date, only for highway shoulders).	Largely unknown; increased cost, need for more resurfacing; potential to reduce stormwater conveyance.	Requires more materials, thicker layers than conventional shoulders; reduced pollutants in water; groundwater recharge.	Cleaner water for surrounding area.
<b>Use and Maintain Pavements that Reduce Urban Heat Island Effects and Reduce Lighting Costs where Warranted by Net Benefits</b>	Where it is determined to be beneficial based on assessment of the life cycle for specific project type and climate region, engineer pavement to reduce heat island effects. <sup>3</sup>	Range of potential costs from net reduction to neutral to net increase if energy savings from air conditioning and lighting are less than pavement alternative life-cycle cost differences.	Increased impact of thickness and materials if not warranted by climate, urban environment, lighting requirements; potential for increased environmental impact of materials designed for thermal characteristics; reduced energy use due to less required lighting.	Less energy use from air conditioning in locations where pavements make substantial contribution to increased urban temperatures in late afternoon and evening.
<b>Consider Fuel Use Due to Structural Responsiveness to Vehicle Loading (Once Research is Completed)</b>	Once calibrated models are available, consider using them to determine where structural responsiveness is significant and develop appropriate strategies based on those results. <sup>3</sup>	Calibrated models will permit evaluation of alternative structures considering traffic, climate and other variables which will allow consideration of both road user and agency costs versus environmental benefits for designs.	Optimization may reduce environmental impact due to less fuel use, particularly on high truck traffic volume routes.	Optimization may improve economic efficiency particularly on high truck traffic volume routes.

Note: For more details on: <sup>1</sup>Materials, including recycled materials, see chapter 3

<sup>2</sup>Construction quality, see chapter 5

<sup>3</sup>Use-phase considerations, see chapter 6

<sup>4</sup>Maintenance and preservation, see chapter 7

<sup>5</sup>Interaction of cost and sustainability, see chapter 10

- Improvements in ME design: reliability. Data and methods for incorporating within-project and between-project as-built variability into design methods will need to be developed. Better consideration of reliability will be needed to consider the effects of increased use of recycled materials, to provide fair comparisons between alternative designs, and to better estimate future maintenance and rehabilitation activities.
- Integration of design and environmental impact analyses. As the pressure for consideration of environmental impacts in the pavement design decision-making process, there will likely be more integration of design, LCCA, and LCA in routine project development. There will be difficulties in balancing multiple design alternatives and selecting the optimal design based on costs (both agency costs and sometimes user costs), sustainability, and constructability. The process laid out in this chapter provides a starting point for agencies to identify major sustainability goals and then develop their own procedures for optimizing alternative design types based on sustainability considerations important to them. Methods for multi-criteria decision making will need to be developed, and this includes the selection of the best design approach for different project delivery environments (DBB with alternative designs, DB, and DBM).
- Development of new materials. Economic, environmental, and political pressures are resulting in much more competition between materials production industries, and potential creation of new industries that reduce the environmental impact of pavements. Increased recycling of pavement materials (such as RAP, RAS and RCA), and the inclusion of co-product materials (such as fly ash and slag cement) will drive much of the competition. Designers will need to consider new laboratory tests, models, and validation studies for newly developed materials as they are introduced by the industry at a faster pace. Specifications will need to be evaluated to ensure that they provide the contractor and materials supplier the flexibility to achieve the desired pavement performance while also maintaining owner/agency costs and risks at an acceptable level.
- Consideration of future maintenance and rehabilitation in design. There will be increased demand to accurately consider future maintenance and rehabilitation as part of the design process in order to provide better inputs to LCC and LCA analyses for both new pavement and major rehabilitation projects. Validated models will be needed for rehabilitation alternatives so that they can be compared on an equal basis. This is essential for DBM projects in order to estimate bid price and risk, but will also be increasingly used for other types of project delivery as well.
- Performance-related construction specifications. It is likely that there will be increased use of performance-related tests for pavement materials and requirements for contractors and materials producers to provide products meeting the properties assumed by the designer using ME design methods. Approaches for developing materials and construction quality specifications that lead to improvements in performance, while still being achievable with available materials and equipment, will be a challenge.
- Better models for smoothness performance. Designers will need to have and use better models for smoothness prediction, particularly as technology for real-time measurement of smoothness at construction is now practical and there is a growing recognition of the importance of smoothness on use-phase environmental impacts (see chapter 6).
- Approaches for designing better performing fully permeable pavements. The technology will likely improve for designing fully permeable pavements that can carry heavier loads and handle stormwater with less space, cost, and difficulty than many current stormwater

management practices. Designers will likely be faced with more opportunities and challenges in using these pavements.

### Concluding Remarks

This chapter describes sustainability considerations through the design process for both new and rehabilitated pavement structures, including structural overlays and reconstruction. It specifically reviews the entire design process and identifies key areas that affect the overall sustainability of the resulting pavement. As noted in previous chapters, there are a number of trade-offs that must be considered, as improvements in one area might be detrimental to another, with the ultimate goals of the owner/agency ultimately determining which approach may be most suitable for a particular project.

The major issues for improving the sustainability of pavements through design decisions are summarized as follows:

- Achieve longer pavement life with the same quantity of materials, or achieve the same pavement life using thinner structures and less materials through design and construction specification decisions.
- Use design and construction specifications to maximize smoothness over the life cycle of the pavement to reduce environmental, economic, and social impacts related to vehicle operations, taking into consideration materials production and construction impacts.
- Consider maximizing the use of recycled materials and minimization of materials transportation where they can produce positive environmental and cost benefits, while not compromising pavement performance.
- Seek to integrate construction and traffic management into design decisions to minimize cost, materials use, and construction-related traffic delay.
- Consider use-phase impacts throughout the life cycle in design, including not only smoothness but other factors as well such as deflection, noise, and stormwater management.

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