GUIDELINES FOR LIMITING DAMAGE TO FLEXIBLE AND COMPOSITE PAVEMENTS DUE TO THE PRESENCE OF WATER

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AMERICAN ASSOCIATION OF
STATE HIGHWAY AND
TRANSPORTATION OFFICIALS

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CHAPTER 1. INTRODUCTION

1.1. Purpose

The purpose of these *Guidelines* is to provide transportation agencies with a concise and comprehensive document that details proven procedures and practices for minimizing damage due to the presence of water in flexible and composite pavement structures. While there is an body of research related to mitigating moisture effects on pavements (e.g., asphalt mix design procedures, incorporation of drainage systems, practices for mitigating freeze-thaw damage), there is no single document that addresses the techniques for limiting pavement damage caused by the presence of water. Therefore, these *Guidelines* have been developed to serve as that document, with a focus on strategies for limiting moisture effects when constructing, maintaining, or rehabilitating flexible and composite pavements.

1.2. Background

Excess moisture and poor drainage conditions have long been recognized as important factors influencing the performance of pavements. Early road-building practices emphasized the need to remove excess water from within and beneath the pavement, and the need to address moisture in pavements is even more critical in today's roadway facilities that carry heavy traffic volumes and high performance expectations.

There are a number of ways in which the presence of water contributes to damage in flexible and composite pavements. Understanding these mechanisms begins with an understanding of the sources of water in pavement structures. Starting with the surface layer, for example, water can enter the pavement structure through cracks, poorly constructed longitudinal joints, and through the interconnected air voids found in open-graded mixtures and poorly compacted dense-graded asphalt layers. Water from the surface or from outside the pavement structure (e.g., from shoulders or from beneath the pavement structure) can contribute to the development of stripping in a low-density asphalt concrete layer, and saturate and weaken the aggregate base and subgrade soil. Moreover, pavement structures that restrict the positive flow of water away from the pavement section (for example, as the result of an improper cross slope or the construction of a "bathtub" pavement section) can be particularly susceptible to moisture damage in the form of weakened pavement layers that can accelerate pavement damage and reduce pavement life.

Not adequately accounting for existing environmental conditions can also adversely affect pavement performance. Examples include insufficient structural depth to account for freeze-thaw conditions, the presence of high or perched water tables, and the presence of water trapped between poorly bonded layers. The resulting pavement deficiencies include increased susceptibility of the pavement materials to the presence of moisture and reduced strength of certain pavement materials when wet or saturated.

In a study conducted by Lu, Harvey, and Monismith (2007), a statistical analysis of condition surveys and field sampling results indicated that air void content, pavement structure, cumulative rainfall, asphalt mix type (dense-graded versus gap-graded rubber modified), anti-strip additive (lime or liquid), and pavement age are all variables that have a significant effect on the amount of pavement damage caused by water. The researchers also concluded that asphalt concrete mixtures with high air voids not only allowed more water intrusion, they also resulted in significantly reduced fatigue life in wet conditions (Lu, Harvey, and Monismith 2007). One of the authors' conclusions was that less-than-optimum asphalt binder content resulted in lower moisture resistance under repeated loading. Other studies have reported that the presence of water in pavement layers adversely impacts the bearing capacity and service life of both asphalt concrete and portland cement concrete pavements (Ceylan et al. 2013; Grover and Veeraragavan 2010). In addition, in cold climates, the adverse effects of water in pavement layers is further magnified due to potential damage from moisture freezing within the surface layer and associated freeze-thaw effects.

1.3. Scope

These *Guidelines* focus on practices and procedures for minimizing damage due to the presence of water in flexible and composite pavements. They describe the potential sources of water that may enter the pavement structure, the distress mechanisms associated with the presence of water, pavement and drainage design features, material type selection, construction activities to minimize pavement damage due to the presence of water, and pavement and drainage system maintenance, preservation, and rehabilitation strategies and activities. The *Guidelines* also include state highway agency (SHA) pavement and drainage Standard Plans or Drawings (Appendix A and B, respectively), Drainage and Pavement Standard Specifications (Appendix C and D, respectively), and fact sheets (Appendix E) related to designing and constructing effective pavement sections and drainage system to minimize damage due to the presence of water.

1.4. Audience

These *Guidelines* are intended for engineers engaged in pavement design, roadway drainage design, construction, and maintenance, as well as technicians, at state highway and local transportation agencies. It provides guidance to agencies in selecting appropriate pavement and drainage features and materials, defining construction activities, as well as suggested maintenance, preservation, and rehabilitation treatments and strategies to minimize damage due to the presence of moisture in flexible and composite pavements.

1.5. Document Organization

The *Guidelines* are organized into the sections as outlined and described in Table 1.1.

1.6. How to Use this Guide

The *Guidelines* can be used by highway and local transportation agencies in the selection of practices and procedures for minimizing damage due to the presence of moisture in flexible and composite pavements, both in new and existing flexible and composite pavements. Answers to the common questions listed in Table 1.2 can be found in the chapters of these Guidelines.

Table 1.1. Document Organization

Chapter	Title	Description
1	Introduction	Provides the purpose, background, scope, audience, and organization of the Guidelines.
2	Sources of Water	Discusses the potential locations where water can enter the pavement structure.
3	DISTRESS Mechanisms	Describes the causes (or mechanisms) that lead to moisture damage and lists common moisture-related distress types.
4	Design Features	Describes the various drainage and pavement features for minimizing damage due to the presence of water.
5	Material Type and Selection	Discusses pavement and drainage materials and properties.
6	**Error! Reference source not found.**	Describes pavement layer and drainage feature construction techniques.
7	Maintenance and Preservation Strategies	Describes pavement surface layer and drainage maintenance and preservation treatments and strategies.
8	Rehabilitation Treatments	Describes pavement and drainage feature rehabilitation treatments.
9	Benefits and Barriers	Summarizes recommended practices, and implementation benefits and barriers.
Appendix A	**Error! Reference source not found.**	Examples of applicable agency standard plans for drainage features.
Appendix B	**Error! Reference source not found.**	Examples of applicable standard plans for pavement features.
Appendix C	**Error! Reference source not found.**	Examples of applicable standard specifications for materials, drainage, and pavement features.
Appendix D	**Error! Reference source not found.**	Summary of agency practices specific to mitigating damage due to water (e.g., practice description, where to use and when, limitations, costs, and benefits).

Table 1.2. Common Questions

	Question	Location
1.	Where does water enter a pavement structure?	Chapter 2
2.	How does the presence of water contribute to pavement distress?	Chapter 3
3.	What pavement and drainage features can be used to minimize damage due to the presence of water?	Chapter 4
4.	What are appropriate drainage and material properties?	Chapter 5
5.	What pavement and drainage features can be considered for new construction?	Chapter 6
6.	What are applicable pavement and drainage system maintenance and preservation activities?	Chapter 7
7.	What are applicable pavement and drainage system rehabilitation treatments?	Chapter 8
8.	What are the benefits of limiting water in the pavement structure before it causes damage?	Chapter 9
9.	Are there any agency standard plans for the pavement and drainage features?	Appendices A and B
10.	Are there any agency standard specifications for the pavement and drainage features	Appendices C and D
11.	Is there any summary data related to agency practices?	Appendix E

1.7. Related Documents

There are a number of useful documents covering various aspects of moisture impacts on pavements and on pavement drainage. The following is a list of some of those key resource documents:

- *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections* (Cedergren, O'Brien, and Arman 1972)
- *Drainage of Highway Pavements* (Johnson and Chang 1984)
- *Moisture Damage in Asphalt Mixtures—A State-of-the-Art Report Drainable Pavement Systems* (Stuart 1990)
- *Pavement Subsurface Drainage Systems* (Christopher and McGuffey 1997)
- *Maintenance of Highway Edgedrains* (Christopher 2000)
- *Drainable Pavement Systems (Instructor's Guide)* (FHWA 1994)

- *Construction of Pavement Subsurface Drainage Systems* (FHWA 2002)
- *Performance of Pavement Subsurface Drainage* (Harrigan 2002)
- *Effects of Subsurface Drainage on Performance of Asphalt and Concrete Pavement* (Hall and Correa 2003)
- *Geotechnical Aspects of Pavements* (Christopher, Schwartz, and Boudreau 2006)
- *Effects of Subsurface Drainage on Pavement Performance: Analysis of the SPS-1 and SPS-2 Field Sections* (Hall and Crovetti 2007)
- *Improved Conditioning and Testing Procedures for HMA Moisture Susceptibility* (Solaimanian, Bonaquist, and Tandon 2007)
- *Moisture Damage to Hot-Mix Asphalt Mixtures* (TRB 2012)
- *Proposed Practice for Alternative Bidding of Highway Drainage Systems* (Maher et al. 2015)

1.8. References

Cedergren, H. R., K. H. O'Brien, and J. A. Arman. 1972. *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*. FHWA-RD-72-30. Federal Highway Administration, Washington, DC.

Ceylan, H., K. Gopalakrishnan, S. Kim, and R. F. Steffes. 2013. *Evaluating Roadway Subsurface Drainage Practices*. IHRP Project TR-643. Iowa Department of Transportation, Ames, IA.

Christopher, B. R. 2000. *Maintenance of Highway Edgedrains*. NCHRP Synthesis 285. Transportation Research Board, Washington, DC.

Christopher, B. R. and V. C. McGuffey. 1997. *Pavement Subsurface Drainage Systems*. NCHRP Synthesis 239. Transportation Research Board, Washington, DC.

Christopher, B. R., C. Schwartz, and R. Boudreau. 2006. *Geotechnical Aspects of Pavements*. FHWA NHI-05-037. Federal Highway Administration, Washington, DC.

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Federal Highway Administration (FHWA). 2002. *Construction of Pavement Subsurface Drainage Systems. Reference Manual.* Federal Highway Administration, Washington, DC.

Grover, S. and A. Veeraragavan. 2010. *Quantification of Benefits of Improved Pavement Performance Due to Good Drainage*. Transportation Research Laboratory, Berkshire, UK.

Hall, K. T. and C. E. Correa. 2003. *Effects of Subsurface Drainage on Performance of Asphalt and Concrete Pavement*. NCHRP Report 499. Transportation Research Board, Washington, DC.

Hall, K. T. and J. A. Crovetti. 2007. *Effects of Subsurface Drainage on Pavement Performance: Analysis of the SPS-1 and SPS-2 Field Sections*. NCHRP Report 583. Transportation Research Board, Washington, DC.

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Johnson, F. L. and F. F. M. Chang. 1984. *Drainage of Highway Pavements*. FHWA-TS-84-202. Federal Highway Administration, Washington, DC.

Lu, Q., J. T. Harvey, and C. L. Monismith. 2007. *Investigation of Conditions for Moisture Damage in Asphalt Concrete and Appropriate Laboratory Test Methods: Summary Report*. UCPRC-SR-2005-01. California Department of Transportation, Sacramento, CA.

Maher, M., G. Hebeler, A. Fuggle, C. Caywood, K. Avery, J. VanKerkhove, and I. D. Moore. 2015. *Proposed Practice for Alternative Bidding of Highway Drainage Systems*. NCHRP Report 801. Transportation Research Board, Washington, DC.

Solaimanian, M., R. F. Bonaquist, and V. Tandon. 2007. *Improved Conditioning and Testing Procedures for HMA Moisture Susceptibility*. NCHRP Report 589. Transportation Research Board, Washington, DC.

Stuart, K. D. 1990. *Moisture Damage in Asphalt Mixtures – A State-of-the-Art Report.* FHWA - RD-90-019. Federal Highway Administration, McLean, VA.

Transportation Research Board (TRB). 2012. *Moisture Damage to Hot-Mix Asphalt Mixtures*. Transportation Research Circular E-C198. Transportation Research Board, Washington, DC.

CHAPTER 2. SOURCES OF WATER

2.1. Introduction

It has long been recognized that saturated subgrade soils can result in rapid pavement deterioration, regardless of the pavement thickness and particularly when combined with heavy truck traffic loadings and moisture-susceptible materials. The primary sources of water that can lead to saturated subgrade soils as well as moisture in other pavement layers include the following (shown schematically in Figure 2.1):

- Water is seeping upward from a high groundwater table due to capillary action or vapor movements.
- Water is flowing laterally from the pavement edge or side ditches.
- Water is seeping from higher ground or underground spring.
- Rain and meltwater is infiltrating through joints and cracks in the pavement surface layers.

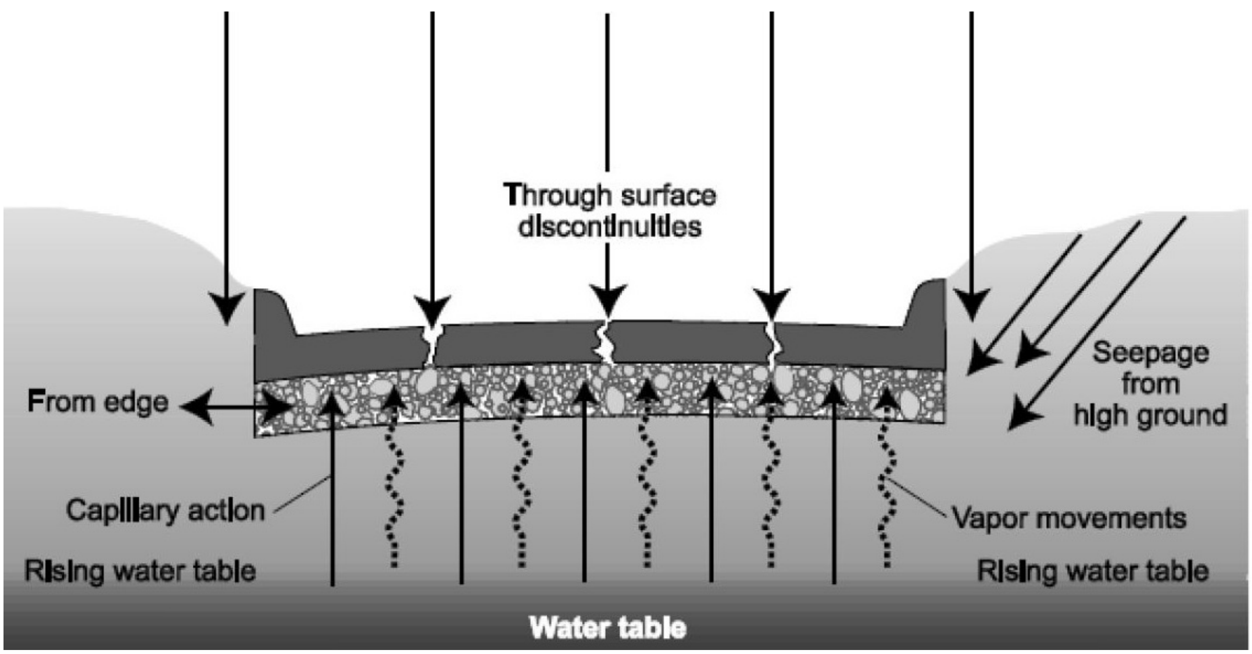

Figure 2.1. Sources of Water (Adapted After Ceylan et al. 2013)

2.2. Surface Infiltration

The main source of moisture in pavements occurs through surface infiltration from rain or melting snow. A study conducted by the Minnesota Department of Transportation (DOT) Office of Materials found that 40 percent of water from rainfall on the pavement surface finds its way into the pavement structure, with the percentage increasing as the pavement gets older (MnDOT 2007). Water from snow and rain can infiltrate the pavement surface through joints, cracks, and pores. Surface water can also enter the pavement structure from the shoulders. When ditch capacity is exceeded, excess water may find its way onto the pavement surface, resulting in surface ponding and increasing the potential for the water to enter the pavement structure (VAA n.d.; Christopher and McGuffey1997; MnDOT 2007; CDOT 2004; Cedergren, O'Brien, and Arman 1972). In general, any situation that promotes standing water on the pavement surface for an extended period, whether it is poor surface drainage more frequent rainfalls, or seasonal flooding, will increase the probability of that water finding its way into the pavement structure.

2.3. Capillary Action and Vapor Movements

The process by which water moves from the groundwater table up to an otherwise dry subgrade soil or unsaturated pavement layer is referred to as capillary action. Capillary action is caused by surface tension and other attractions developed in the soil that essentially *wick* moisture up from an underlying water table. During freezing temperatures, the water from capillary action can freeze and result in ice lenses in the soil. When the ice lenses are localized or develop nonuniformly, the resulting frost heave can severely damage the pavement structure (MnDOT 2007). Moisture can also be present in pavement materials in the form of water vapor (VAA n.d.). Moisture, in the form of vapor, can move upward in the pavement system from aggregate and subgrade soil layers (Santucci 2010). Water vapor is typically found in the air voids of the pavement structure and usually only plays a very small role as a source of moisture (MnDOT 2007). Water that infiltrates the pavement structure through either of these forms will usually rise until an impervious layer is reached. Unless proper drainage is provided, it will accumulate below the impervious layer (VAA n.d.).

2.4. Changes in Depth to Water Table

Groundwater levels typically fluctuate with changes in season and changes in precipitation. During the winter and spring months, water from melting snow seeps through the natural soil and contributes to raising the water table. In the summer, the water table depth may decrease due to moisture migration from the water table in to the unsaturated subgrade material via capillary action. The water table depth may also decrease due to the extraction of water from nearby wells. In contrast, the groundwater table depth may rise several feet after a heavy rain storm (MnDOT 2007; VAA n.d.). If the presence of groundwater is not correctly identified and addressed during the pavement design process, it can significantly affect pavement performance and slope stability (CDOT 2004).

2.5. Seepage from High Ground

In some places, pavements are found at lower elevations than the surrounding area, such as in mountainous or hilly locations where it was more convenient to construct the pavement along the low prevailing terrain. Gravity flow usually brings water into the pavement from higher ground if there is water present at the higher ground (Santucci 2010; MnDOT 2007; CDOT 2004). If the pavement is located on a hillside, water seeping from higher ground may flow through the pavement unless it encounters an impervious layer. If the pavement is located in a valley where there are hills on either side of the pavement, water may seep into the pavement and create a ponding effect. In some severe cases, such as after heavy rain storms, the pavement might be fully submerged under water. Recent heavy rainfall and subsequent flooding in various regions of the US have contributed to serious and unexpected pavement problems (Gaspard 2019, https://www.omaha.com/news/local/state-oks-emergency-repairs-to-flood-damaged-roads-around-omaha/article_6ac4bb3c-481c-54ce-86db-c53af267c630.html)

2.6. Infiltration from Pavement Edge

Water may seep into the pavement laterally through openings on the pavement edge and ditches. The lack of proper pavement edge drainage will allow water to sit on the pavement edge for extended periods of time (Figure 2.2). This ponding effect will allow moisture to infiltrate the pavement structure along the pavement edge. Excessive irrigation may also contribute to moisture infiltration through the pavement edge (Santucci 2010; MnDOT 2007).

Figure 2.2. Ponding of Water after Heavy Rain

2.7. Summary

There are many ways moisture can enter a pavement structure. The most common one is surface infiltration where moisture enters the pavement structure from the top. Moisture can also enter the pavement by capillary action, vapor movements, rising groundwater table, seepage from grounds at higher elevation, and openings around the pavement edge.

2.8. References

Cedergren, H. R., K. H. O'Brien, and J. A. Arman. 1972. *Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Sections*. FHWA-RD-72-30. Federal Highway Administration, Washington, DC.

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Minnesota Department of Transportation (MnDOT). 2007. *Pavement Design Manual*. Minnesota Department of Transportation, St. Paul, MN.

Santucci, L. 2010. *Minimizing Moisture Damage in Asphalt Pavements*. Pavement Technology Update, Volume 2, Number 2. Technology Transfer Program, Richmond, CA.

Virginia Asphalt Association (VAA). n.d. *Pavement Drainage*. Virginia Asphalt Association, Richmond, VA.

CHAPTER 3. DISTRESS MECHANISMS

3.1. Introduction

For every type of pavement distress, there is an underlying causal mechanism. Some mechanisms are simple and some can be complicated. In the case of transverse cracking in a flexible pavement, for example, the underlying mechanism is the development of tensile stresses in the pavement as it tries to contract during cold temperatures. When the thermal-related tensile stress exceeds the strength of the asphalt concrete, a crack initiates and ultimately progresses across the entire width of the pavement. Moisture damage is more complicated because it manifests itself in different types of distress that have different mechanisms. It is important to understand these mechanisms so that they can considered when selecting the best method to address the moisture damage problem. Four primary distress mechanisms that contribute to moisture damage are described in the following sections.

3.2. Material Softening/Weakening Mechanism

The most common distress mechanism associated with water in a pavement is softening or weakening of unbound subsurface layers (i.e., base, subbase, and subgrade soil). Water can also weaken bound layers, including asphalt concrete, but not to the extent of unbound layers. The typical sources of moisture associated with this mechanism include surface infiltration, percolation from high ground, and seepage from the pavement edge. As water infiltrates the unbound subsurface materials, it coats and lubricates the particles and allows them to move more freely around each other. With increasing moisture levels, the unbound materials lose their capacity to distribute applied loads and will not provide adequate support to the surface layer.

Other factors that affect the softening mechanism associated with water infiltration include the following:

- **Material type—**Subgrade soil materials such as silt and clay are more susceptible to moisture than sandy and gravelly materials. Clays are especially sensitive because of their affinity to absorb moisture and to expand.
- **Particle microtexture—**Aggregate particles that have a rough surface texture are better able to resist the lubricating effects of water because of the higher friction between the particles.
- **Material gradation—**Dense-graded materials generally have fewer voids and do not take on as much moisture as open-graded, gap-graded, or uniformly-graded materials.

The common types of distress in asphalt concrete pavements that can result from this mechanism include permanent deformation (both rutting and depressions), fatigue cracking, base/subgrade soil failure (Figure 3.1), and potholes. For composite pavements, the common types of distress include pumping and reflection cracking.

Figure 3.1. Subgrade Soil/Base Failure and Fatigue Cracking Resulting from Heavy Moisture Infiltration

3.3. Frost Heave Mechanism

As water freezes it expands, increasing in volume by as much as 9 percent. Frost heave refers to the uplift of a pavement that can occur as water in subgrade soils freeze and expand. The upward movement is particularly a problem when it occurs next to fixed structures like bridges that do not uplift or when nonuniform uplifting creates problems with road roughness.

Like the material softening mechanism, the frost heave mechanism is also one that ultimately results in high levels of moisture and loss of load-bearing capacity in the unbound subsurface layers. Three conditions must be present for the frost heave mechanism to occur (Christopher, Schwartz, and Boudreau 2006; WSDOT 1995):

- **Frost penetration**—Extended periods of subfreezing temperatures that result in frost penetrating deep into the subgrade soil.
- **Source of moisture**—The typical source of moisture is a water table within 3 m (10 ft) of pavement surface. However, the depth of influence is dependent on soil type and depth of freeze.
- **Frost-susceptible soil**—These are subgrade soils such as clays, silts, and other combinations of fine-grained materials that have poor drainage characteristics, wick water from an underlying water table, and tend to freeze quickly.

Table 3.1 summarizes the typical strength and drainage characteristics for different soil classifications.

Table 3.1. Summary of Subgrade Soil Characteristics (Adapted from Yoder and Witczak 1975)

Soil Classification		Description	Subgrade Soil Strength[1]	Drainage Characteristics
Gravel and Gravelly Soils	*GW*	Well-graded gravels or gravel-sand mixtures, little to no fines	Excellent	Excellent
	GP	Poorly graded gravels or gravel-sands mixtures, little or no fines	Good to excellent	Excellent
	GM	Silty gravels, gravel-sand silt mixtures	Good to excellent	Fair to poor
	GC	Clayey gravels, gravel-sand-clay mixture	Good	Poor to practically impervious
Sand and Sandy Soils	*SW*	Well-graded sands or gravelly sands, little or no fines	Good	Excellent
	SP	Poorly graded sands or gravelly sands, little or no fines	Fair to good	Excellent
	SM	Silty sands, sand-silt mixtures	Fair to good	Fair to poor
	SC	Clayey sands, sand-clay mixtures	Poor to fair	Poor to practically impervious
Silts and Clays with Liquid Limit < 50	*ML*	Inorganic silts and very fine sand, rock flour, silty or clayey fine sand or clayey silts with slight plasticity	Poor to fair	Fair to poor
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Poor to fair	Practically impervious
	OL	Organic silts and organic silty clays or low plasticity	Poor	Poor
Silts and Clays with Liquid Limit > 50	*MH*	Inorganic silts, micaceous or diatomaceous fine sand or silty soils, elastic silts	Poor	Fair to poor
	CH	Inorganic clays of high plasticity, fat clays	Poor to fair	Practically impervious
	OH	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Practically impervious
Highly Organic Soils	*(Pt)*	Peat and other highly organic soils	Not suitable	Fair to poor

[1] When not subject to frost action.

If any of the three conditions listed is removed, frost heave will be eliminated or at least minimized (WSDOT 1995).

Figure 3.2 illustrates the formation of ice lenses in a pavement section that lead to frost heave. Through capillary action, moisture from an unfrozen subgrade migrates vertically through the pavement structure. When the unfrozen moisture reaches the plane of freezing temperature, the larger void spaces filled with water will begin to freeze. With sustained freezing temperature, ice crystals form and attract moisture from adjacent void spaces. Continued ice crystal growth develops into ice lenses, which in turn exerts vertical pressure and results in surface heaving.

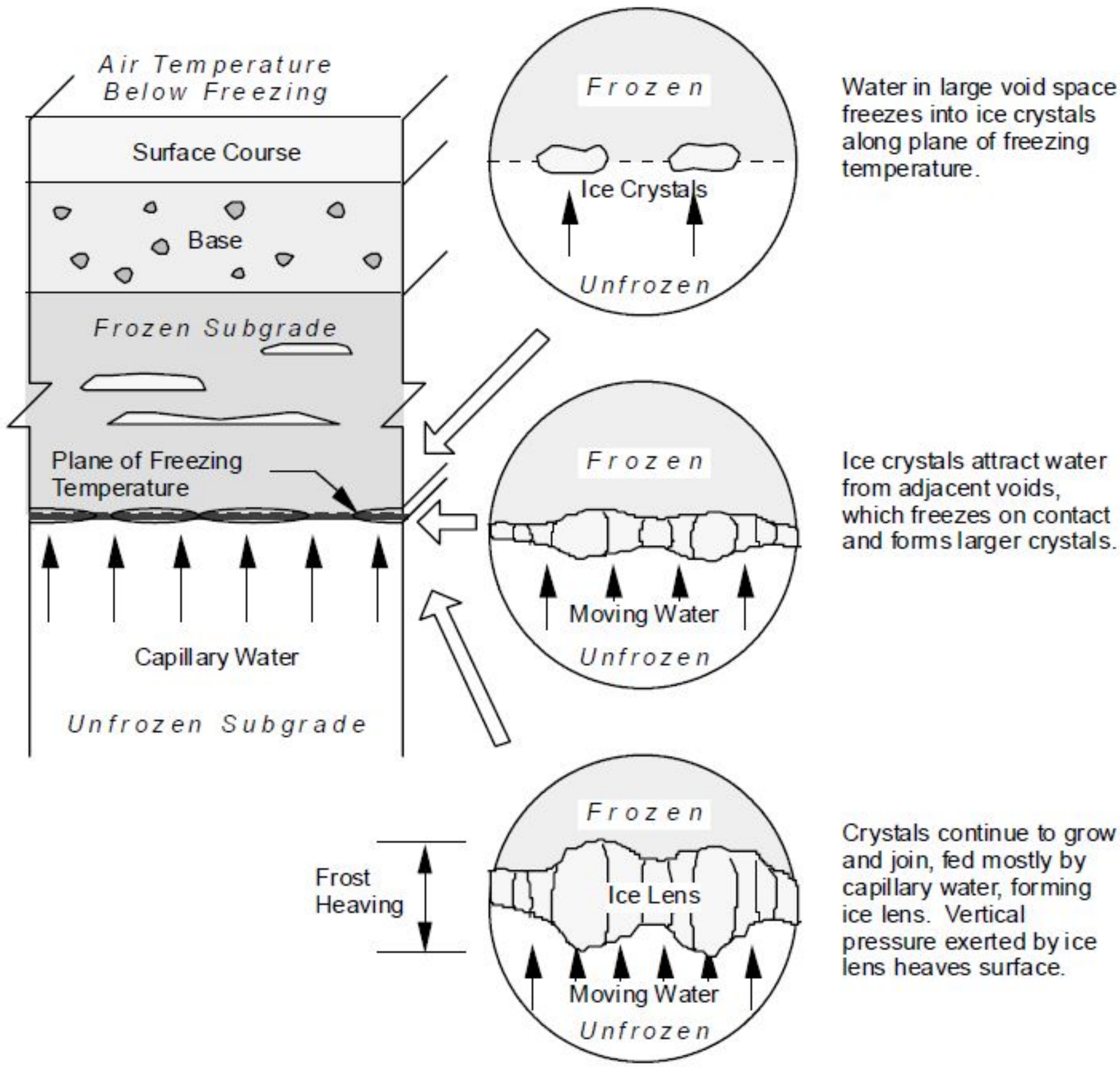

Figure 3.2. Mechanics of Frost Heave (WSDOT 1995)

As seasons change from winter to spring and temperatures rise, all the ice lenses will eventually thaw and create high moisture contents in the subgrade soil and other subsurface layers. During these spring-thaw conditions, the moisture contents often approach saturation and are almost always high enough to significantly reduce the bearing capacity of the affected materials. As with the softening/weakening mechanism, the common distress types in asphalt concrete pavements include permanent deformation (both rutting and depressions), fatigue cracking, base/subgrade failure, and potholes (Figure 3.3). For composite pavements, the common types of distress include pumping and reflection cracking.

Fatigue cracking (courtesy of WSDOT)

Potholes in wheel paths

Figure 3.3. Examples of Pavement Damage Due to Freezing and Thawing

Very fine sands and silts are most susceptible to frost heave because of their ability to draw water to considerable heights. Clays also have considerable suction potential and are also susceptible to frost heave if their plasticity index is less than about 10 to 12. Figure 3.4 shows the types of soils (and their combinations of capillarity and permeability) that are most susceptible to frost heave (ACPA 2007).

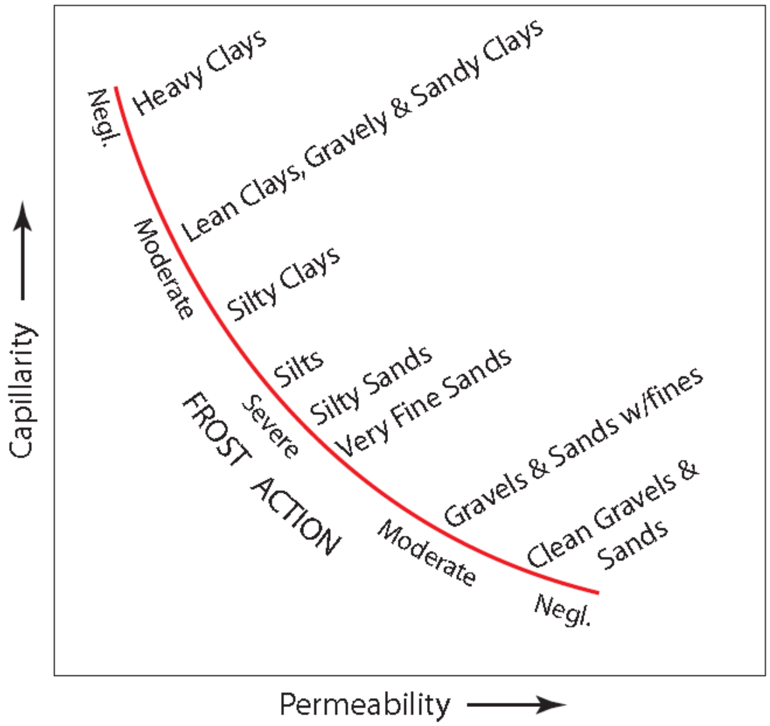

Figure 3.4. Frost Susceptibility of Soils is a Function of Capillarity and Permeability (ACPA 2007)

3.4. Stripping Mechanism(s)

Stripping in asphalt concrete pavements can be described as the breakdown of the bond between the asphalt binder and the aggregate in the mix as a result of the exposure to moisture. In an FHWA report (Stuart 1990), for example, stripping is described as “the displacement of asphalt films from aggregate surfaces that occurs when the aggregate has a greater affinity for water than the asphalt.” This basic description is satisfactory for the purposes of these Guidelines; however, it is useful to recognize that there are different mechanisms that can contribute to this phenomenon. Based on a review of the literature at the time, Little and Jones (2003) identified six primary mechanisms that can contribute to stripping in the asphalt concrete:

- **Detachment—**Separation of an asphalt film from an aggregate surface by a thin film of water without an obvious break in the film (this is the classic stripping mechanism).
- **Displacement—**Similar to detachment, displacement differs because it involves displacement of asphalt at the aggregate surface through a break in the asphalt film.
- **Spontaneous emulsification—**Process by which water droplets become emulsified in asphalt cement.
- **Pore pressure—**Refers to the increased pore pressures developed in entrapped water as a result of repeated load traffic applications.
- **Hydraulic scour—**Process that occurs on the pavement surface as a result of the action of moving tires on a saturated surface. Water is sucked under the tire into the pavement by the tire action.

- **pH instability—**Process by which adhesion between the asphalt and aggregate is affected by the pH of the contact water.

For any given situation, there is likely to be more than one of these mechanisms acting simultaneously. In addition, some may interact to further accelerate deterioration.

Figure 3.5a shows a core from an asphalt concrete pavement that has undergone stripping. The disintegration of the asphalt concrete layer and the presence of exposed aggregate surfaces are classic symptoms of a stripping problem. Figure 3.5b shows an asphalt concrete pavement in which stripping has resulted in high-severity fatigue cracking. Other common distresses that can develop as a result of a stripping problem include rutting, bleeding, potholes, raveling, cupping (surface depression on either side of a crack), and surface layer debonding. The latter distress, debonding (or delamination), is most often related to an inadequate application of an asphalt emulsion (tack) prior to overlay placement. However, it can also be the result of most of the stripping mechanisms, namely detachment, displacement, spontaneous emulsification, increased pore pressures during trafficking, and pH instability. Figure 3.6 shows an asphalt concrete pavement in which a slurry seal surface layer has debonded because of prolonged exposure to moisture.

a. Stripping in an asphalt concrete core b. Fatigue cracking resulting from stripping

Figure 3.5. Asphalt Concrete Stripping (Photos Courtesy of Washington State DOT)

Figure 3.6. Debonding/Delamination of Slurry Seal Due to Prolonged Exposure to Water

There are several factors that can affect the degree of moisture damage and stripping resulting from the presence of water in the pavement (Kandhal and Richards 2001):

- **Type of aggregate—**Composition (degree of acidity or pH, surface chemistry, types of minerals, source of aggregate), physical characteristics (angularity, surface roughness, surface area, gradation, porosity, permeability), dust and clay coatings, moisture content, and resistance to degradation
- **Type of asphalt—**Grade or hardness, chemical composition, crude source, and refining process
- **Mixture design and construction—**Air void level and compaction, permeability and drainage, and film thickness
- **Environment—**Temperature, freeze-thaw cycles, moisture vapor, dampness, pavement age, and presence of ions in the water
- **Traffic—**Traffic loading and frequency

Each of these should be considered when assessing the extent of the stripping problem and, ultimately, in determining the preferred course of action to mitigate the problem.

3.5. Pumping Mechanism

As the name implies, this moisture damage mechanism involves water displacement and saturated material through a pumping action created by moving wheel loads. This mechanism is normally associated with jointed plain concrete pavements (JPCP), but can also occur in composite pavements if the conditions are severe enough. These severe conditions include the following (Hoerner et al. 2001):

- Presence of erodible (fine-grained) material is in the layer beneath the concrete slab.
- Saturated conditions are in the layer beneath the concrete slab.

- Poor load transfer at a transverse joint or mid-panel crack that lead to high deflections.

Figure 3.7 provides a profile view of a pavement that is helpful in describing this mechanism. As a heavy vehicle travels down the road, the wheel loads will induce pore water pressures in the saturated layer. The increase in pore water pressure under the approach slab will be significant, but generally not enough to cause the movement of material. However, as the wheel load travels across the transverse joint (or mid-panel crack), there is a sudden increase in pore water pressure beneath the leave slab that is enough to cause the water and saturated fines to be pumped upwards along the lateral edge joint. Figure 3.8 shows a concrete pavement that is experiencing a severe pumping problem.

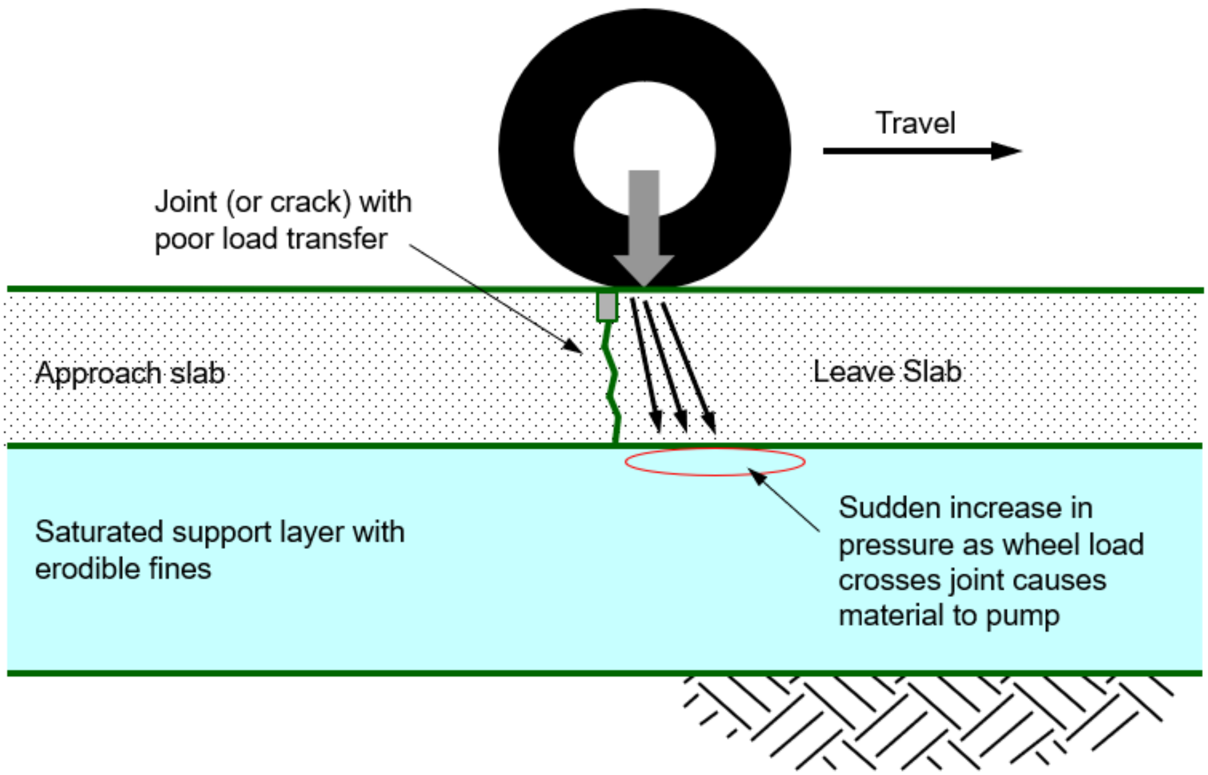

Figure 3.7. Diagram Illustrating the Pumping Mechanism

Figure 3.8. High-Severity Pumping Along Edge of Concrete Pavement

Because the asphalt concrete surface improves load transfer and helps reduce moisture infiltration, the in situ conditions for pumping are typically less severe for composite pavements than for concrete pavements. However, it is still possible for pumping to occur.

Other forms of distress that can occur as a result of the pumping mechanism include faulting, subsurface voids, and loss of support (Hoerner et al. 2001). However, these are less likely to occur in composite pavements.

3.6. Moisture-Related Distress Types in Asphalt Concrete and Composite Pavements

Table 3.2 and 3.3 (Christopher, Schwartz, and Boudreau 2006) provide a summary of moisture-related distress types in asphalt concrete and composite pavements, respectively. In addition to listing the distress types, these tables also provide information that should be helpful in addressing the distress mechanism.

Table 3.2. Summary of Moisture-Related Distress in Asphalt Pavements (Christopher, Schwartz, and Boudreau 2006)

Type	Distress Manifestation	Moisture Problem[1]	Climatic Problem[2]	Material Problem[3]	Load Associated Distress[4]	Structural Defect Begins in:[5]		
						Asphalt Layer	Base Layer	Subgrade
Surface Deformation	Bump or distortion	Excess moisture	Frost heave	Volume increase	No	No	No	Yes
	Corrugation or rippling	Slight	Moisture and temperature	Unstable mix	Yes	Yes	Yes	No
	Stripping	Yes	Moisture	Loss of Bond	No	Yes	No	No
	Rutting	Excess in granular layers or subgrade	Moisture	Plastic deformation, stripping	Yes	Yes	Yes	Yes
	Depression	Excess moisture	Suction & materials	Settlement, fill material	No	No	No	Yes
	Potholes	Excess moisture	Moisture, temperature	< Strength > Moisture	Yes	Yes	Yes	Yes
Cracking	Longitudinal	No; but accelerates	No	Construction	No	Faulty construction	No	No
	Fatigue (alligator)	Yes; accelerates	Spring thaw, strength loss	Thickness	Yes	Yes, mix	Yes	No
	Transverse	No; but accelerates	Low temperature; freeze-thaw cycles	Thermal properties	No	Yes, temperature susceptible	No	No
	Slippage	Yes	No	Loss of bond	Yes	Yes, bond	No	No

[1] Moisture problem indicates the extent to which moisture can contribute to the distress.
[2] Climatic problem indicates the climate components that can contribute to the distress.
[3] Material problem identifies the materials-related factors that can contribute to the distress.
[4] Load associated distress indicates whether wheel loading contributes to the distress.
[5] Location where structural defect begins indicates the layer of the pavement where structural deterioration usually begins.

Table 3.3. Summary of Moisture-Related Distress in Composite Pavements (Adapted from Christopher, Schwartz, and Boudreau 2006)

Type	Distress Manifestation	Moisture Problem[1]	Climatic Problem[2]	Material Problem[3]	Load Associated Distress[4]	Structural Defect Begins in:[5]		
						AC/PCC	Base	Subgrade
Surface Deformation	Stripping	Yes	Moisture	Loss of Bond	No	Yes (AC)	No	No
	Rutting	Excess in granular layers or subgrade	Moisture	Plastic deformation, stripping	Yes	Yes (AC)	Yes	Yes
	Potholes	Excess moisture	Moisture, temperature	< Strength > Moisture	Yes	Yes (AC)	Yes	Yes
	Blow up	No	Temperature	Thermal properties	No	Yes (PCC)	No	No
	Pumping & Erosion	Yes	Moisture	Inadequate strength	Yes	No	Yes	Yes
	Faulting	Yes	Moisture suction	Erosion settlement	Yes	No	Yes	Yes
	Curling/ warping	Yes	Moisture & temperature	Moisture & temperature differentials	No	Yes (PCC)	No	No
Cracking	Longitudinal (AC layer)	No; but accelerates	No	Construction	No	Faulty AC construction	No	No
	Fatigue (alligator)	Yes; accelerates	Spring thaw, strength loss	Thickness	Yes	Yes, AC mix	Yes	No
	Transverse (AC layer)	No; but accelerates	Low temperature; freeze-thaw cycles	Thermal properties	No	Yes, AC temperature susceptible	No	No
	Slippage	Yes	No	Loss of bond	Yes	Yes, AC bond	No	No
	Cracking (PCC layer)	Yes	Moisture	Follows erosion	Yes	No	Yes	Yes

[1] Moisture problem indicates the extent to which moisture can contribute to the distress.
[2] Climatic problem indicates the climate components that can contribute to the distress.
[3] Material problem identifies the materials-related factors that can contribute to the distress.
[4] Load associated distress indicates whether wheel loading contributes to the distress.
[5] Location where structural defect begins indicates the layer of the pavement where structural deterioration usually begins.

3.7. Summary

As pavements age, they experience a variety of climate- and load-related stresses that ultimately lead to different types of distress and deterioration that can seriously affect their performance. Accordingly, when designing a new pavement or maintaining/rehabilitating an existing pavement, it is important to consider the causes and mechanisms of the distress. Otherwise, it is likely that the distresses will develop (or redevelop) at a high rate. This chapter provides information on the key distress mechanisms that contribute to moisture damage in asphalt concrete and composite pavements. Understanding these mechanisms enables the engineer to develop better pavement designs and select appropriate maintenance and rehabilitation treatments that will minimize the adverse effects of moisture on pavement performance.

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CHAPTER 4. DESIGN FEATURES

4.1. Introduction

There are three main approaches for controlling or reducing moisture problems in pavements (Christopher, Schwartz, and Boudreau 2006):

- **Prevent moisture from entering the pavement system**—Techniques for preventing moisture from entering the pavement include providing adequate cross slopes and longitudinal slopes for rapid surface water runoff and sealing all cracks, joints, and other discontinuities to minimize surface water infiltration.
- **Use materials and design features that are insensitive to the effects of moisture**—Materials that are relatively insensitive to moisture effects include granular materials with few fines, cement-stabilized and lean concrete bases, and asphalt-stabilized base materials. Design features for flexible pavements include full-width paving to eliminate longitudinal joints, asphalt-stabilized base layers, and use of a subbase to reduce erosion and promote drainage. Appropriate design features for rigid pavements include dowel bars and widened slabs to reduce faulting and inclusion of a subbase between the base and subgrade to reduce erosion and promote bottom drainage.
- **Quickly remove moisture that enters the pavement system**—A variety of different drainage features are available for removing excess moisture. For example, underdrains and ditches are designed to permanently lower the water table under the pavement, while permeable bases and edgedrains are designed to remove surface infiltration water.

This chapter addresses the various types of pavement design features associated with the three main approaches to address a moisture damage problem.

4.2. Roadway Geometric Design

Among the factors that play a role in minimizing the damaging effect of water on pavements, roadway geometric design is one of the most important. By selecting the right geometric features in the roadway design process, surface water can be more efficiently transported (or drained) from the pavement. This means that water will have less of an opportunity to infiltrate the pavement and weaken the underlying layers. It will also help reduce the potential for wet-weather accidents. The different aspects of roadway geometric design that affect pavement drainage are discussed in the following sections.

4.2.1. Cross Slope

Cross slope refers to the transverse or lateral slope of the pavement surface. It is typically classified in one of two categories – uniform and crowned. Uniform-sloped sections slope to the same shoulder while crowned sections slope to opposite shoulders (FHWA 2002). When compared to uniform slopes, the use of crowned pavement sections will reduce the required time to drain water by half. While cross slopes used on paved roadways may range from 1.5 to 3 percent, the standard cross slope on roadways should be 2 percent per successive lane and should not exceed 4 percent (AASHTO 2011). Typical cross slopes on shoulders range from 3.5 to 6 percent (Yu et al. 1998).

Even with the best of intentions, there are locations on the roadway where the cross slope might be reduced to zero. One typical location is at the transition area of horizontal curves where the superelevation is being developed. At this point, the cross slope will be zero and this might create conditions that prohibit water from flowing. Installation of a drainage system, such as a transverse drain and outlet, may be required to aid the flow of water off the pavement surface (FHWA 1994).

If the roadway cross slope is toward the median of the roadway, more drainage inlets will be needed to remove the water from the passing lanes. The value of this is that it will reduce the amount of surface water on the driving lanes (AASHTO 2011).

4.2.2. Longitudinal Slope

The longitudinal slope of a roadway is commonly referred to as the grade. A minimum grade ranging from 0.3 to 0.5 percent is typically used. There are locations on the roadway, however, where the longitudinal slope or grade may be reduced to zero. Two typical examples are at the bottom of a sag curve and on a long, flat tangent section of roadway. In the case of a sag vertical curve, the longitudinal slope of the roadway might be reduced to zero at the bottom of the curve. This forces water from both sides of the curve to drain down into the sag curve and create a ponding effect. This scenario is also evident at low-water crossing locations. Installation of a drainage system, such as a transverse drain and outlet, may be required to prevent the ponding effect that may occur at the bottom of a sag curve after a heavy rainfall. On roadways built on flat or level locations, the grades are typically very close to or equal to zero. These roadways depend almost entirely on the cross slope of the roadway for drainage. Additional drainage features, such as transverse underdrains, should be considered if cross slopes are insufficient (FHWA 2002). The maximum recommended grades based on design speed and roadway location are provided in Table 4.1 (AASHTO 2011).

Table 4.1. Maximum Recommended Grades (AASHTO 2011)

	Design Speed, mi/h (km/h)				
Design Section	**30 (48)**	**40 (64)**	**50 (80)**	**60 (96)**	**70 (112)**
Rural Sections, Maximum Grade, %					
Level	–	5	4	3	3
Rolling	–	6	5	4	4
Mountains	–	8	7	6	5
Urban Sections, Maximum Grade, %					
Level	8	7	6	5	–
Rolling	9	8	7	6	–
Mountains	11	10	9	8	–

4.2.3. Length of Drainage Path

The length of the drainage path (for water moving along the roadway surface) is an important consideration because of its effect on the amount of time required for water to flow off the surface. The length of the drainage path is a function of the grade, slope, and width of the roadway. Equations 4.1 and 4.2 may be used to determine the length (L) and the slope of the flow path (S) (Arika, Canelon, and Nieber 2009).

$$L = \sqrt[W]{1 + \left(\frac{g}{S_c}\right)^2} \qquad \text{Eq. (4.1)}$$

$$S = W\sqrt{{S_c}^2 + g^2} \qquad \text{Eq. (4.2)}$$

where:

W = width of the pavement (from crown to pavement edge),
g = longitudinal grade of the roadway, and
S_c = roadway cross slope.

4.2.4. Curb and Gutter and Shoulders

A curb and gutter system serves more than one purpose on the roadway. It aids in access control of vehicles and separates pedestrians from vehicle traffic. From a drainage perspective, a curb and gutter system collects and removes storm water runoff from the pavement and reduces the potential for water to infiltrate pavement subsurface layers. Curb and gutter systems are mostly used in areas where vehicle operating speeds are relatively slow, such as on arterials, collectors, and residential streets in urban areas (Caltrans 2012).

Two of the more important considerations when designing a curb and gutter system (and their accompanying drainage inlets) are the *frequency* of the runoff event (or recurrence interval) and the *spread* of water on the pavement. The spread of water refers to the distance that water will “back up” away from the curb during a runoff event. Anytime the spread is large enough to encroach on a traffic lane, there will be increased risk of traffic accidents and delays for the traveling public. Accordingly, the design for the curb and gutter system is intended to balance the risk with the cost of increased drainage capacity. Other design factors that come into consideration in the design of a curb and gutter system are highway classification, design speed, shoulder width, and projected traffic growth (Johnson and Chang 1984). Figure 4.1 shows that the risks associated with water on traveling lanes increases with increasing speeds, traffic volumes, and higher highway classifications.

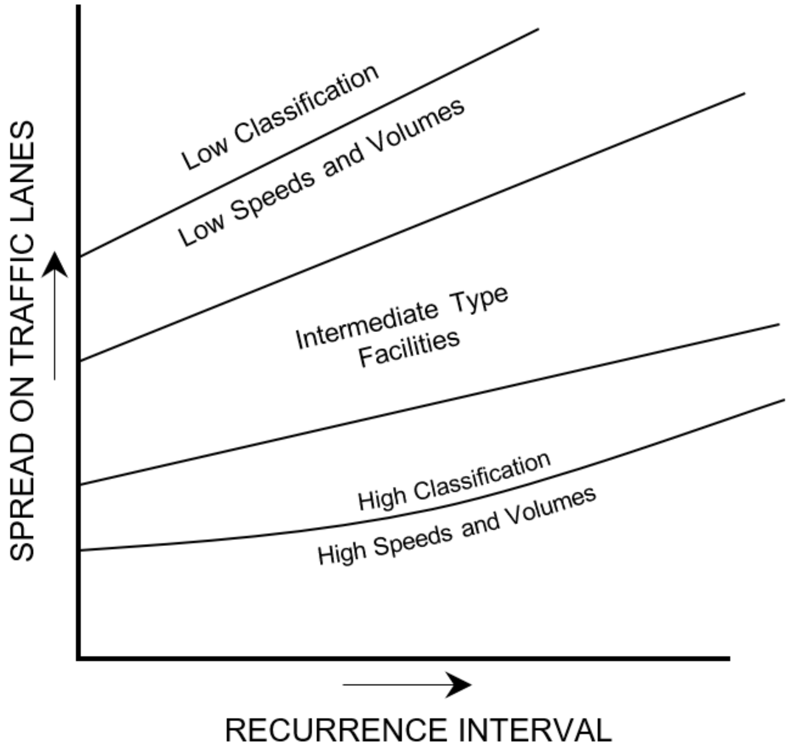

Figure 4.1. Relationship of Highway Classification, Traffic Volumes and Speeds, and Design Storm Frequency and Spread (Johnson and Chang 1984)

In areas with higher vehicle operational speed, shoulders may be used to allow water to flow away from the driving lanes and minimize the amount of moisture infiltration along the edge of the outside lane. Shoulders with cross slopes greater than that of the traveling lanes should be used to quickly remove water from the roadway. As discussed previously, typical shoulder cross slopes range from 2 to 5 percent. A situation where the shoulder cross slope should be similar to the cross slope of the adjacent travel lane is where snow removal operations are common. In these cases, the similar cross slope between the traveling lanes and shoulders allows the efficient removal of snow from the lanes and shoulders (Caltrans 2012).

4.3. Subsurface Drainage

For highway and other types of pavements, subsurface drainage systems are needed to help capture and remove free water that is not captured (or not fully captured) by surface drainage. This includes free water that has entered the pavement through cracks, infiltration, seepage from high ground, high water table, and adjacent springs. If not removed, this free water can potentially contribute to moisture damage in the pavement (Ridgeway 1982). It is difficult to identify every location where moisture will accumulate beneath the pavement and create a problem. Consequently, subsurface drainage systems are usually needed for pavements constructed in moisture-prone environments and are expected to serve significant amounts of traffic. Although the use of subsurface drainage systems can help avoid the risk of premature pavement failure due to excess moisture, there are some conditions where they may not be required. Following are recommended criteria for determining roadway locations where surface drainage may be adequate (Cedergren, O'Brien, and Arman 1972):

- The average annual precipitation is less than 254 mm (10 in.).
- The lateral drainage transmissibility of the base layer directly beneath the pavement surface layer is 100 times greater than the design infiltration rate.
- The combined lateral drainage transmissibility of the base and the vertical drainage capability of all underlying materials exceeds the design infiltration rate.

Note that these criteria apply only to free water from surface or lateral sources. A subsurface drainage system may still be called for if the origin of excess moisture is a high water table or other underground source.

Table 4.2 provides more detailed criteria that can be used to determine the need for some method of subsurface drainage. The criteria include climate condition, level of truck traffic, and permeability of the existing subgrade soil. The latter is important because it accounts for the natural "drainability" of the soil where the pavement is being constructed.

Table 4.2. Need for Subsurface Drainage (Adapted from Christopher, Schwartz, and Boudreau 2006)

Climatic Condition	< 2.5 Million 20-Year Design Lane Heavy Trucks			2.5 to 12 Million 20-Year Design Lane Heavy Trucks			> 12 Million 20-Year Design Lane Heavy Trucks		
	Subgrade Permeability (ft/day)								
	<10	10-100	>100	<10	10-100	>100	<10	10-100	>100
Wet-Freeze	F	NR	NR	R	R	F	R	R	F
Wet-No Freeze	F	NR	NR	R	F	F	R	R	F
Dry-Freeze	NR	NR	NR	F	F	NR	F	F	NR
Dry-No Freeze	NR	NR	NR	NR	NR	NR	F	NR	NR

Notes:
R = some form of subdrainage or other design features are recommended to combat potential moistures problems.
F = providing subdrainage is feasible. Additional factors to consider include:
(1) past pavement performance and experience in similar conditions (if any).
(2) cost differential and anticipated increase in service life through the use of various drainage alternatives.
(3) anticipated durability or erodibility of paving materials.
NR = subsurface drainage is not required in these situations.
Wet-freeze = annual precipitation > 20 in; annual freezing index > 150 °F days.
Wet-no freeze = annual precipitation > 20 in; annual freezing index < 150 °F days.
Dry-freeze = annual precipitation < 20 in; annual freezing index > 150 °F days.
Dry-no freeze = annual precipitation < 20 in; annual freezing index < 150 °F days.

4.3.1. Types of Subsurface Drainage

Following is a description of the four main types of pavement subsurface drainage systems. These are applicable to both flexible and composite pavement pavements.

4.3.1.1. Permeable Bases

Permeable bases are stabilized or unstabilized aggregate layers located directly under the bound pavement surface layer and are intended to remove water seeping through the surface of the pavement. A separator layer, which may be a geotextile or an aggregate layer, is typically placed below the permeable base to separate it from the subsurface pavement layers or the underlying subgrade soil. When properly installed, the separator layer will help maintain the separation of the two layers so that fine materials from below do not infiltrate the aggregate layer and so that particles from the aggregate layer are not pushed into the underlying layer from wheel loading.

Unstabilized permeable bases contain more fine-sized aggregates for stability while stabilized permeable bases develop their stability by the binding action of the stabilizing material (Moulton, 1980). Both stabilized and unstabilized materials should consist of durable and angular crushed stone with no fine aggregate passing the No. 200 sieve. Crushed aggregates used in permeable bases should have at least two mechanically fractured faces. The aggregates used in permeable bases are typically expected to have no more than 45 percent of L.A. Abrasion wear. For permeable bases that are constructed in regions with freeze-thaw cycles, the durability of the aggregates used should be tested for soundness. These aggregates are typically expected to have a soundness loss not exceeding 18 percent (FHWA 1994; FHWA 2002).

For stabilized permeable bases, the asphalt content of the permeable base layer should be carefully selected to provide the necessary strength and stability. Because of their prolonged exposure to moisture over time, stabilized permeable bases must also be able to resist mixture stripping. For aggregates that are prone to stripping, anti-strip additives may be added to help improve the adhesion of the asphalt to the aggregate. Typical asphalt contents for asphalt stabilized base courses are in the range of 2 to 3 percent by weight. It is important that stabilized permeable bases not be over compacted, otherwise the mix will become less permeable and less able to serve its function. Most state highway agencies specify 1 to 3 passes of a 4.5 to 9 MT (5 to 10 ton) steel-wheeled roller (FHWA 1994; FHWA 2002).

4.3.1.2. Edgedrains

Edgedrains are typically placed along the outside edge of the pavement, parallel to the pavement centerline and in contact with the permeable base layer so that it can intercept and carry away the exiting water before it infiltrates the pavement structure (MnDOT 2007). If a permeable base layer is not present in the pavement structure, the depth of the edgedrain should be close to the bottom of the subbase layer, but above the subgrade (WIDOT 2013).

There are three main types of edgedrains:

- **Aggregate trenches**—These trenches are lined with a geotextile filter fabric, filled with a highly permeable backfill material, and graded so that water will flow towards specifically located exit pipes. The filter fabric helps reduce the infiltration of fine materials that can clog the trench.

- **Aggregate trench with slotted or perforated pipe**—This type of edgedrain is basically an aggregate trench with slotted or perforated pipe installed along the bottom to permit increased water flow towards carefully located outlet pipes.
- **Geocomposite fin drains**—This type of edge drain involves the use of a unique type of drain pipe to intercept moisture and transport it to outlet pipes. The pipes are typically rectangular shaped and are delivered in large spools. The pipes consist of a structural core that serves as a conduit for water and as a skeleton for the geotextile covering. The geotextile covering allows water to permeate into the core while preventing the infiltration of fine particles.

Out of the three, aggregate trenches with perforated pipes are the most used because of their higher flow capacity and ease of maintenance (FHWA 2002). The pipes used as edgedrains can be made up of metallic or plastic materials. Edgedrains should be used along both shoulders of all permeable base installations except in areas where the permeable base is day-lighted. Edgedrains should also be placed at an elevation higher than the water table so that they do not provide storage to groundwater and allow the formation of frost lens in the pavement during freezing temperatures (NYDOT 2002). Outlet pipes should be adequately spaced along the path of the edgedrain so that water can be directed out of and away from the pavement structure (Arika et al. 2009). The required pipe capacity and outlet spacing must be carefully determined so that water can flow freely from the system. Some of the design methods that can be used are discussed in subsequent sections. Figure 4.2 shows a diagram of a typical edgedrain installation with a permeable base and a trench with slotted pipes (FHWA 2002).

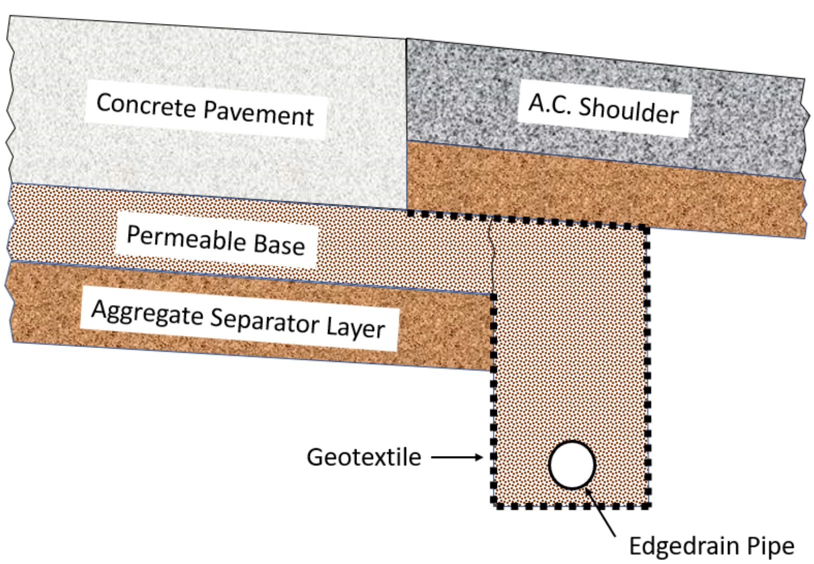

Figure 4.2. Typical Configuration of an Edgedrain (adapted from FHWA 2002)

4.3.1.3. Underdrains

Underdrains, also known as deep drains, are porous pipes installed to prevent groundwater from entering the pavement by lowering the groundwater level and draining slopes. They are typically installed in narrow trenches lined by aggregates that are able to protect the drain pipe from being crushed (NYDOT 2002).

4.3.1.4. Horizontal drains

Horizontal drains, also known as cross drains and transverse drains, are narrow drains that are placed transverse to the centerline of the roadway. Horizontal drains can be used to transfer water from one side of the roadway to the other in areas where only one edge of the pavement has edgedrains. Horizontal drains can also be used in downhill areas where water seeps through the pavement. Figure 4.3 shows a plan view of a typical horizontal drain.

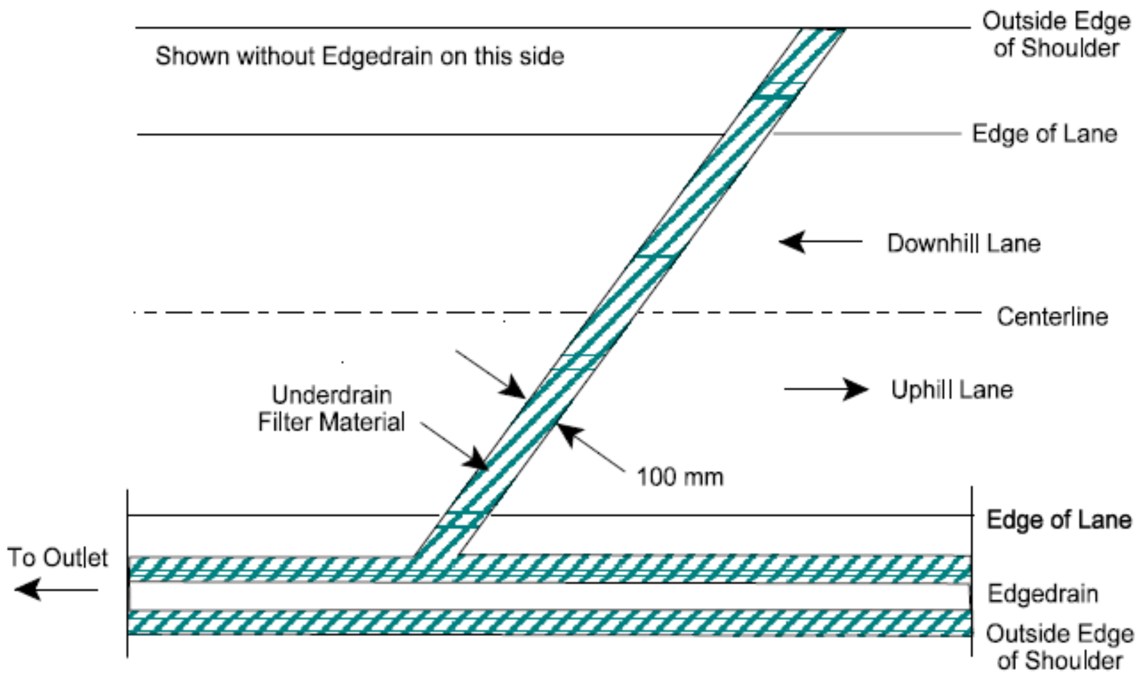

Figure 4.3. Typical Horizontal Drain (NYDOT 2002)

4.3.2. <u>Summary of Drainage Design Procedures</u>

There are several tools available to design subdrainage systems. Some of these tools are basic mathematical equations that can be used to estimate such design factors as surface flow, infiltration rates, and drainage times, while others are computer models that can be used to determine key design factors and the associated design elements of the drainage system. Five design methods that are commonly used to estimate drainage needs are briefly discussed here: the Rational Method, Infiltration Ratio Method, Time to Drain Method, DRIP, and PAVDRN. The latter two are computer models that are commonly used for drainage design.

4.3.2.1. The Rational Method

This method is used to design storm water drainage systems and it is a simple method used to compute the peak surface runoff rate. Equation 4.3 is at the center of this method (Brown et al. 2009; Johnson and Chang 1984):

$$Q = CIA/K_U \qquad \text{Eq. (4.3)}$$

where

Q = peak surface runoff rate, m^3/s (ft^3/s),
K_U = units conversion factor, 360 for metric (1 for U.S. customary),
C = runoff coefficient of the watershed (dimensionless),
I = average rainfall intensity, mm/h (in./h), and
A = drainage area, hectares, ha (acres).

The runoff coefficient is a dimensionless number that defines the amount of water that becomes runoff after a rainfall event. This coefficient is dependent on the type of surface material and relative steepness of the slopes. Values may range from 0.1 (parks) to 0.95 (inner city areas). The average rainfall intensity is the intensity of a design storm for a predetermined duration and frequency, and is a function of the storm duration and frequency. The duration of the storm is typically selected to be the time a volume of water needs to reach from the farthest corner of the drainage to the nearest storm water inlet. The storm frequency defines the amount of time between storm events of a given magnitude. For example, a storm with a frequency of 50 years signifies that a storm of this magnitude happens, on average, once every 50 years. It is important to select the proper design storm frequency. A selected frequency that is too low might lead to the design of storm water inlets that are regularly overwhelmed by storms. Conversely, a selected frequency that is too high will lead to the construction of a more expensive drainage system that is not fully utilized. The drainage area refers to the area of the watershed that contributes to the peak runoff.

4.3.2.2. The Infiltration Ratio Method

This method is used to estimate the amount of water that enters or infiltrates the pavement. Equation 4.4 is at the center of this method (FHWA 1992):

$$q_i = 2CR \qquad \text{Eq. (4.4)}$$

where

q_i = pavement infiltration, m^3/day/m^2 of pavement (ft^3/day/ft^2 of pavement),
C = infiltration ratio (dimensionless), and
R = rainfall rate, mm/h (in/h).

A design storm frequency of 2 years and a duration of 1 hour are recommended because rainfall intensities under this design storm represent the average worst storm that occurs each year (FHWA 1994). The infiltration ratio is the portion of rainfall that enters the pavement structure through surface cracks or joints. Typical values of C for asphalt pavements range from 0.33 to 0.5 (FHWA 1994). For composite pavements in which the underlying joints and cracks have reflected through the asphalt concrete surface, C values will range between 0.5 and 0.67, depending on the width of the reflected crack.

4.3.2.3. Time to Drain Method

This method is used to estimate the amount of time required to drain a permeable base. In this method, it is assumed that rainwater will infiltrate the pavement until the permeable base is full. After that, rainwater will continue to flow on the pavement surface as runoff. The time it takes the permeable base to drain is used to assess the quality of the permeable layer. The time to drain can be calculated by Equation 4.5 (FHWA 1992):

$$t = T * m * 24 \qquad \text{Eq. (4.5)}$$

where

t = time to drain, h,
T = time factor, and
m = "m" factor.

The time factor, T, is based on the geometry of the base course and can be determined using a design chart (Figure 19, FHWA 1992). This design chart requires a slope factor (S_1) which can be calculated using Equation 4.6:

$$S_1 = \frac{L_R * S_R}{H} \qquad \text{Eq. (4.6)}$$

where

S_1 = slope factor (dimensionless),
H = thickness of base, m (ft),
L_R = resultant length of base, m (ft), and
S_R = resultant slope of base, m/m (ft/ft).

The "m" factor is calculated using Equation 4.7:

$$m = \frac{N_e * L_R^2}{k * H} \qquad \text{Eq. (4.7)}$$

where

N_e = effective porosity (dimensionless),
k = coefficient of permeability, m/day (ft/day), and
L, H, R = previously defined.

Table 4.3 shows AASHTO's recommendations of the time to drain 50 percent of the drainable water based on the overall quality of the drainage system (AASHTO 1993).

Table 4.3. Recommended Quality of Drainage (AASHTO 1993)

Rating	Time to Drain
Excellent	2 hours
Good	1 day
Fair	7 days
Poor	1 month
Very Poor	Does not drain

4.3.2.4. DRIP Software

DRIP (Drainage Requirements In Pavements) is a software program that can be used to evaluate several different pavement drainage characteristics and features (Mallela et al. 2002):

- **Roadway geometry**—Calculates the true length and slope of the drainage path from uniform sloped and crowned roadway sections.
- **Sieve analysis**—Calculates effective grain sizes, effective porosities, coefficient of uniformity and gradation, and coefficient of permeability of any gradation used in pavement design.
- **Inflow calculations**—Calculates surface water infiltration using infiltration rational approach and crack infiltration approach.
- **Permeable base design**—Users can develop design for permeable bases using either depth-of-flow or time-to-drain methodologies.
- **Separator layer design**—Users can determine if a separator layer is required based on the gradation of the permeable base and subgrade conditions. Users can also design separator layers using geotextiles or aggregate materials.
- **Edgedrain design**—Users can design edgedrains using geocomposite fin drains or pipe edgedrains.

4.3.2.5. PAVDRN Software

This software was designed to be used by highway design engineers to determine the likelihood of hydroplaning on roadways. It allows users to compute the longest flow path length over the design roadway section and determines the water film thickness at various points on the flow path. The calculated water film thickness is used to determine the vehicle speed at which hydroplaning will occur. The vehicle speed can then be compared to the design speed of the roadway. PAVDRN allows users to minimize the drainage path length and reduce the water film thickness by incorporating design features such as porous asphalt pavements, grooving, and appurtenances to remove water from the surface (Anderson et al. 1998).

4.3.3. Design Considerations

Designing adequate drainage for pavement systems is a very important part of the overall pavement design process. Key design considerations are listed below:

- **Groundwater table**—The location of the groundwater table and its fluctuations throughout the year should be considered while designing the pavement structure. If the level of the groundwater table creates a risk of infiltration into the pavement structure, underdrains should be considered to remove the groundwater. The base and subbase layer thicknesses can also be increased so that the pavement structure is thicker and the top layers are elevated.
- **Precipitation**—The amount of precipitation, either in the form of rain or snow, has a major impact on drainage design. Certain geographic regions may not experience frequent or abundant precipitation while other regions receive a great deal of precipitation. In areas with significant storm events, the use of permeable base layers should be considered. The Time to Drain method can be used to ensure adequate drainage capacity. It is also important to provide sufficient cross slopes so that water can easily flow off of the surface layer.
- **Terrain**—It is important to consider the terrain around the pavement structure when designing drainage systems. For example, horizontal drains may be necessary to allow the lateral flow of water through a pavement structure located in a mountainous region; however, horizontal drains are not necessarily needed if the pavement is located on level terrain.

4.3.4. Subsurface Drainage Considerations

Following are some additional design considerations for subsurface drainage systems (Christopher, Schwartz, and Boudreau 2006; NYSDOT 2002):

- **Permeable bases**—Permeable bases are typically used to drain subsurface water resulting from surface infiltration. The captured moisture is directed to a side ditch by either daylighting the base or by installing longitudinal edgedrains with outlets. Permeable bases should contain very few fines (material passing No. 200 sieve) to allow for a more free-draining system.

- **Stormwater drainage system**—The size and number of stormwater inlets should be adequate to handle the anticipated surface flows. Also, the inlet elevation should be low enough to accept inflow without backing up. The edge drain inlet should be at least 150 mm above the 10-year storm flow line in the drainage structure.
- **Dry well**—When a stormwater system is not possible or practical, the designer should consider an outlet to a dry well, which is a trench built to temporarily store and release water. The dry well always outlets to a ditch or other outlet. This option is only valid if the dry well is above the water table.
- **Raise grade and create ditches**—In low-lying areas where water routinely collects or ponds, the designer should consider raising the elevation of the cross section (when site conditions permit) and then creating side ditches.
- **Daylight base layer**—If the roadway is constructed on an embankment with ditches, the permeable base layer may be daylighted to produce a continuous water outlet. If the distance to the ditch is not too long, this option will generally be less expensive and require less maintenance than installing a formal edge drain system. The potential problem with this drainage approach is that the edge of daylighted layer may be rendered ineffective by silt or by overgrown vegetation in the daylight zone. Accordingly, regular maintenance will likely be required to maintain the effectiveness.
- **Frost penetration**—The designer should consider the depth of frost penetration when designing a subsurface drainage system. Some systems (e.g., permeable bases) will lose their effectiveness if filled with frozen water.

4.4. Pavement Design

A subsurface drainage system is a critical factor that impacts the long-term performance of pavements. Although standardized performance metrics to quantify the benefits of drainage systems have not been established, the use of permeable, free-drying outlet systems have generally resulted in good performance (Ridgeway 1982).

While the surface layer is the most significant layer for pavement performance, the underlying layers play a critical role in the performance of the surface layer. For example, the stiffness of the subgrade layer is a direct input into most pavement design procedures and it has a direct impact on the pavement thickness design. If the subsurface drainage systems are unable to drain water, they lose strength and this weakens the entire pavement structure and can cause premature failure (Christopher, Schwartz, and Boudreau 2006; NYSDOT 2002).

This section summarizes the key aspects of pavement design, including the last two AASHTO pavement structural design procedures, subgrade stabilization, base type selection, design considerations related to asphalt and composite pavements, surface type considerations, and shoulder design considerations.

4.4.1. Summary of Pavement Design Procedures (New and Rehabilitation)

In the U.S., there are a number of procedures available for the design of both new and rehabilitated asphalt concrete pavements and asphalt concrete overlays on existing PCC pavements (i.e., composite pavement rehabilitation design). The most widely used design procedures in the U.S., however, are the AASHTO *Guide for Design of Pavement Structures* (AASHTO 1993), often referred to as the AASHTO Design Guide, and AASHTOWare Pavement ME design, which is based on the *Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (AASHTO 2015). Both methods have been used to develop new pavement designs and rehabilitation designs and both have features that allow them to consider the impact of the various types of subgrade soil treatment, pavement materials, and drainage features on structural design.

4.4.1.1. AASHTO Design Guide

The AASHTO Design Guide includes a procedure for the structural design of flexible pavements that takes into consideration several factors, including: a) the stiffness (resilient modulus) of the subgrade soil, b) the expected level of truck traffic over a specified design period (as represented by 80 kN (18,000 lb) equivalent single axle load applications), c) the planned reduction in pavement condition over time (as represented by the loss of pavement serviceability index [PSI]), and d) the desired design reliability (a factor that accounts for design uncertainty). Application of the design equation yields a minimum required structural number (*SN*) for the pavement. To complete the design, the designer must select a combination of pavement layer materials and thicknesses that, together, meet the minimum *SN* requirement. The *SN* for a given combination of layer materials and thicknesses is determined using Equation 4.8:

$$SN = a_1 * D_1 + a_2 * D_2 * m_2 + a_3 * D_3 * m_3 \qquad \text{Eq. (4.8)}$$

where

a_1, a_2, a_3 = layer coefficients for layers 1, 2, and 3,
D_1, D_2, D_3 = thicknesses (in.) for layers 1, 2, and 3, and
m_2, m_3 = drainage coefficients for layers 2 and 3.

The layer coefficients are dependent upon the load-carrying ability of the material that makes up the layer. For example, a good-quality, hot-mix asphalt layer has a relatively high layer coefficient of 0.44, while an unbound granular subbase course may have a relatively low layer coefficient of 0.10. The drainage coefficient for a given layer is used to account for the sensitivity of the layer material to moisture exposure. If a layer is susceptible to moisture or is likely to be exposed to moisture for prolonged periods, the drainage coefficient will be less than 1. Thus, the effect of a low drainage coefficient will be a need to increase the pavement structure or to improve the drainage environment (preferably the latter, as increased pavement thickness is not a panacea for poor drainage conditions).

4.4.1.2. AASHTOWare Pavement ME

AASHTOWare Pavement ME, commonly known as Pavement ME, is a state-of-the-art method of designing pavements. It allows pavement designers to compute critical pavement responses, such as stresses and strains, by analyzing the structure using engineering mechanics. Pavement ME allows for a more rigorous design, especially if the software program has been calibrated for local use and if the pavement designer is able to provide more detailed material properties and traffic loading. Pavement designers can also use default values; however, results obtained using default values are not necessarily applicable since the default values were derived using national averages. Pavement ME can analyze a trial design for the design period and evaluate the performance by using predicted amounts of load and environment-related cracking and predicted IRI. These predicted performance values can be compared to allowable values to see if the pavement was designed adequately. Numerous trial designs can be performed until satisfactory results are obtained.

4.4.2. Subgrade Soil Stabilization

Of all the layers that make up a pavement structure, the subgrade soil is almost always the weakest and most susceptible to moisture exposure. Because of this, protection of the subgrade soil from overstress (due to vertical wheel loading) and exposure to moisture has become a key consideration in the pavement design process.

If the subgrade soil is determined to be too weak or too susceptible to moisture, there are a variety of stabilization options that can be employed to correct the problem. Removing and replacing a portion of a defective subgrade soil with a more competent material is an option. However, it may not be the most desirable option because of the increased excavation, haul, and material disposal, the increased time of construction, and overall higher cost.

Another category of options that can be used effectively as part of a new pavement construction project is soil stabilization. This method is usually applied for three reasons (Christopher, Schwartz, and Boudreau 2006):

- Provide a construction platform to dry very wet soils and facilitate compaction of the upper layers. For this case, the stabilized soil is usually not considered a structural layer in the pavement design process.
- Strengthen weak soils and restrict the volume change potential of a highly plastic or compressible soil. For this case, the stabilized soil is usually given a structural value in the pavement design process.
- Reduce moisture susceptibility of fine-grained soils (i.e., clays, silts, and most of their combinations).

Table 4.4 provides a list of most of the most common methods for stabilizing a subgrade soil as part of a new pavement construction project. For each method, the table shows the primary type of soil to which it is applicable and the intended improvement to the soil. As can be seen, each method of subgrade soil stabilization falls under one of three general categories: mechanical, admixture, and water proofers. These are summarized below based on details provided in the *Geotechnical Aspects of Pavements* Reference Manual (Christopher, Schwartz, and Boudreau 2006).

Table 4.4. Stabilization Methods for Pavements (Adapted from Rollings and Rollings [1996])

Stabilization Method		Soil Type	Improvement	Remarks
Mechanical	*Additional gravel*	Silts and clays	None	Reduces dynamic stress level
	Blending	Moderately plastic	None	Too difficult to mix
		Other	Improve gradation Reduce placidity Reduce breakage	
	Geosynthetics	Silts and clays	Strength gain through minimum disturbance and consolidation	Fast, plus provides long-term separation
	Lightweight fill	Very weak silts, clays, and peats	Thermal barrier for frost protection	Fast and reduces dynamic stress level
Admixture	*Portland cement*	Plastic	None	Less pronounced hydration of cement
		Coarse	None	Hydration of cement
	Lime	Plastic	Drying Strength gain Reduce plasticity Coarse texture Long-term pozzolanic cementing	Rapid reaction for all improvements, except pozzolanic cementing is a slow reaction
		Coarse with fines	Same as plastic	Dependent on quality of plastic fines
		Non plastic	None	No reactive material
	Lime-fly ash and lime-cement-fly ash	Same as lime	Same as lime	Covers broader range
	Bituminous	Coarse	Strengthen Binder waterproof	Asphalt cement or liquid asphalt
		Some fines	Same as coarse	Liquid asphalt
		Fine	None	Difficult or unable to mix
	Pozzolanic and slags	Silts and coarse	Acts as a filler Cementing of grains	Dense and strong Slower than cement
	Chemicals	Plastic	Strength increase Volume stability	See vendor literature Difficult to mix
Water Proofers	*Asphalt*	Plastic and collapsible	Reduce change in moisture	Long-term moisture migration problem
	Geomembranes	Plastic and collapsible	Reduce change in moisture	Long-term moisture migration problem

4.4.2.1. Mechanical Stabilization Techniques

This generally refers to a process of soil stabilization in which select gravel or granular materials are either constructed on top of the existing soft or wet subgrade soil or mechanically blended into it. It also includes the use of geosynthetic materials, such as geotextiles and geogrids, which are placed between the subgrade soil and a granular layer. These mechanical methods work best with clays, silts, and some organic peat materials.

1. **Addition of gravel layer**—When good quality gravels are placed and compacted in the form of a thick blanket over a weak subgrade soil, the gravel layer can reduce the vertical stress on the subgrade soil and create a sound working platform for construction equipment (Christopher, Schwartz, and Boudreau 2006). However, it is important that the material be crushed so that there will be better interlock between the aggregate particles and a corresponding wider distribution of the vertical loading. Because of the thickness (typically 457 to 762 mm [18 to 30 in.]) and lower thermal conductivity (as compared to most frost-susceptible soils), the gravel layers will also provide increased protection against frost penetration and frost heaving of the subgrade soil. If used in conjunction with a geosynthetic material, the combination can also help maintain the long-term structural integrity of the gravel layer by keeping it from penetrating into the weak subgrade soil. It is important to note that unless this layered approach involves the use of either an impervious geotextile or well-draining aggregate layer that will reduce moisture infiltration, it will not have much impact on the relative strength of the subgrade soil. It is also important to note that the addition of a gravel layer is generally not the most cost-effective method and it may be worth considering other stabilization techniques.
2. **Blending gravel into subgrade soil**—The process of blending gravel or recycled pavement material with poor quality subgrade soils works well with soils that are only moderately plastic. The incorporation of gravel into weak subgrades can help stabilize the soil and create a good working platform for construction equipment and for construction of the new pavement. If sufficient gravel is blended with the soil, it will help create dryer conditions and decrease the influence of the soil’s plasticity. However, it should be noted that the gravel-soil blend may lose much of its support characteristics if it becomes saturated.
3. **Use of geosynthetic materials**—Geotextile fabrics and geogrids are frequently used to help stabilize a subgrade soil because of their ability to perform one or more of four functions (Koerner 1990):
   - **Separation**—Fabrics help maintain the separation between a weak material (such as wet, fine-grained subgrade soil) and a structural layer (such as an aggregate base material). By preventing the aggregate in the structural from infiltrating the weak material, the fabric will help the structural layer maintain its structural integrity.
   - **Reinforcement**—Geogrids (and to a certain extent, fabrics) help confine an aggregate material, minimize its decompaction after construction, and reduce the long-term loss of structural strength.

- **Filtration**—Woven fabrics (or filter fabrics) will allow the passage of moisture into a drainage layer, while preventing the infiltration of fine-grained soil materials that would eventually clog the drainage layer and render it ineffective.
- **Drainage**—In addition to the permeable fabrics, there are various types of impermeable fabrics (mostly treated) that can be used in subsurface drainage applications that involve capturing and redirecting the flow of water away from the pavement and into a ditch or subsurface drain.

The cost of using geosynthetic materials is not insignificant; however, if a geotextile fabric or geogrid can help prevent a premature pavement failure or reduce future maintenance requirements, the initial cost will be more than justified. More information on geosynthetic materials and their use in pavement drainage applications is provided in Chapter 5 (Section 5.3).

It should be noted that design procedures are available for the use of geosynthetic materials in stabilizing the subgrade soil beneath a pavement structure (Koerner 1990; Holtz et al. 1998). The design approach described in *Geosynthetic Design and Construction Guidelines* (Holtz et al. 1998) is a detailed, eight-step process that considers such factors as the strength of the soil, the soil classification, the location of the groundwater table, the thickness of aggregate base, and the characteristics of the geosynthetic material.

4. **Use of lightweight fill materials**—Under item 1, the use of thick gravel layers is described as a means of bridging over a weak soil to reduce the vertical stresses and provide a working platform. The problem with gravel layers in some instances is that their weight can lead to consolidation and settlement of the weak soil. In these instances, the use of a lightweight fill material may prove to be a good alternative. Table 4.5 provides a list of the typical lightweight fill materials and shows their range in compacted density and approximate cost (Christopher, Schwartz, and Boudreau 2006).

Although the mechanical methods of stabilization do provide strength improvement over the original weak subgrade soil conditions, this increase is generally not considered in the design of the pavement section (Christopher, Schwartz, and Boudreau 2006). However, this does not mean that the strength added to the structure cannot be considered. As with other structural layers of the pavement, the designer has the option of assigning some structural value to the improvement and then determining how much additional structure is required to satisfy the vehicle loading requirements. The designer should exercise caution in characterizing the structural value of the improvement, given that its properties may decay over time.

Table 4.5. Typical Lightweight Fill Materials and Their Associated Densities and Unit Costs (Adapted from Christopher, Schwartz, and Boudreau 2006)

Fill Type	Range in Density	Approximate Cost
Geofoam (EPS)	0.2 to 0.5 kN/m^3 (1 to 3 lb/ft^3)	\$54 to \$114/m^2 (\$45 to \$95/yd^2) [1]
Foamed Concrete	4.7 to 14.1 kN/m^3 (30 to 90 lb/ft^3)	\$54 to \$72/m^2 (\$45 to \$60/yd^2)
Wood Fiber	7.9 to 14.1 kN/m^3 (50 to 90 lb/ft^3)	\$16 to \$26/m^2 (\$13 to \$22/yd^2)[1]
Shredded Tires	8.6 to 13.4 kN/m^3 (55 to 85 lb/ft^3)	\$26 to \$39/m^2 (\$22 to \$33/yd^2)[1]
Expanded Shale and Clay	8.6 to 14.9 kN/m^3 (55 to 95 lb/ft^3)	\$54 to \$72/m^2 (\$45 to \$60/yd^2)[2]
Fly ash	16.5 to 21.2 kN/m^3 (105 to 135 lb/ft^3)	\$18 to \$30/m^2 (\$15 to \$25/yd^2)[2]
Boiler Slag	14.9 to 25.1 kN/m^3 (95 to 160 lb/ft^3)	\$3 to \$5/m^2 (\$3 to \$4/yd^2)[2]
Air-Cooled Slag	15.7 to 22.0 kN/m^3 (100 to 140 lb/ft^3)	\$9 to \$12/m^2 (\$8 to \$10/yd^2)[2]

[1] Price includes transportation and placement cost.
[2] FOB plant.

4.4.2.2. Soil Stabilization Through the Use of Admixtures

As shown in Table 4.4, different admixtures can be mixed with subgrade soils to improve strength characteristics and control the potential for soil swelling and frost heave. Of the different admixtures shown, only three are considered good candidates for the stabilization of poor-quality subgrade soils. Following are descriptions of the basic soil conditions for which the three types of admixture are applicable. These are based on the information presented in the *Geotechnical Aspects of Pavements* Reference Manual (Christopher, Schwartz, and Boudreau 2006):

- **Portland cement**—Cement is a widely used admixture to improve the strength, stiffness, plasticity, and frost susceptibility of low-plasticity clays, sandy soils, and granular soils. The improvement in these properties is dependent on the cement content. At low cement contents (generally less than 3 percent of the dry weight of soil), the stabilized soil is referred to as a cement-modified soil. For higher cement contents (in the range of 3 to 10 percent of the dry weight of the soil), the stabilized material is referred to as soil-cement or cement-treated subgrade. These materials will have an unconfined compressive strength of at least 1034 kPa (150 psi).
- **Lime**—The use of hydrated lime as an admixture to improve soil properties is separated into two processes:
  - Lime treatment (or lime modification) is typically used to help dry the soil and allow for compaction. It can also be used to treat expansive soils (i.e., soils that exhibit swell in excess of 3 percent). The application rate is usually in the range of 1 to 3 percent and the depth of treatment generally in the 0.6- to 0.9-m (2- to 3-ft) range. The process results in a material that can support construction traffic, although the increase in strength is not high enough to impact the pavement structural design.

- Lime stabilization is similar to lime treatment in that it is effective at drying the soil, improving workability, and reducing the swell potential of fine-grained soils, including highly plastic clays. However, since it involves higher lime contents (typically in the range of 3 to 8 percent of the dry weight of soil), the stabilized material will also exhibit significant increases in strength (i.e., unconfined compressive strengths of at least 345 kPa [50 psi] after 28 days). Soils classified as CH, CL, MH, ML, SC, and GC with a plasticity index greater than 12 and with 10 percent passing the No. 40 sieve are usually suitable for lime stabilization.

- **Lime-fly ash (LF) and lime-cement-fly ash (LCF)**—LF and LCF are best suited for stabilizing course-grained soils and granular materials having little to no fines. When mixed with lime and water, the fly ash forms a hard, cementitious paste that binds the aggregate particles together and produces relatively high compressive strengths. Unlike the admixture design for lime and cement, the design using lime and fly ash is intended to overfill the voids between the aggregate particles and create a strong matrix that does not rely on point to point contact between the soil particles.

The process for admixture design is basically the same for the three admixtures described above. The nine basic steps presented in the *Geotechnical Aspects of Pavements Reference Manual* (Christopher et al. 2006) are shown below:

- **Step 1**—Classify soil to be stabilized.
- **Step 2**—Prepare trial mixes with varying admixture content.
- **Step 3**—Develop moisture-density relationship for initial design.
- **Step 4**—Prepare triplicate samples and cure specimens at target density.
- **Step 5**—Determine index strength.
- **Step 6**—Determine resilient modulus for optimum percent admixture.
- **Step 7**—Conduct freeze-thaw tests.
- **Step 8**—Select percent additive to achieve minimum design strength and freeze-thaw durability.
- **Step 9**—Add 0.5 to 1.0 percent to admixture content to compensate for non-uniform mixing.

4.4.3. Base Type Selection

The primary purpose of the base layer in a flexible pavement structure is to distribute wheel load stresses over a wider area so that they do not overstress the underlying subbase and soil layers. The base layer can also help improve subsurface drainage and protect the subgrade soil from frost penetration. For subsurface drainage, a permeable base layer may be used below the asphalt concrete surface layer to capture and transport water to a side ditch or edge drain. In these cases, the base layer must be carefully designed to ensure that positive drainage is achieved over the expected service life of the pavement. This includes placing filter fabric to keep the base layers from clogging and maintaining free flow from these layers by installing properly designed edgedrains or “daylighting” the base layer to an adjacent ditch (Van Dam et al. 2015).

Various types of base layers (such as unbound aggregate base, aggregate separator layer, asphalt- or cement-treated base, asphalt or cement-treated permeable bases, and so on) can be used below the surface layer in the pavement structure. Before selecting the type of material to be used, the designer should ensure that the aggregate material provides good mechanical interlock and meets the following requirements (Christopher, Schwartz, and Boudreau 2006):

- Aggregate should have at least two fractured faces and should consist of 98 percent crushed stone.
- The L.A. abrasion wear should be at most 45 percent (determined by AASHTO T 96 test method).
- Soundness should not exceed 12 to 18 percent (determined by AASHTO T 104 test method).
- For permeable bases, the gradation should ensure free movement of water with a minimum permeability value of approximately 300 m/day (1000 ft/day) and the material passing No. 40 sieve should be non-plastic (according to AASHTO T 90 Test Method).

More information on the requirements for gradation, durability, and soundness is provided in Section 5.2.1.

4.4.4. Specific Design Considerations for Asphalt Pavements

Specific considerations in asphalt pavement design are summarized below:

1. **Environmental impacts**—Temperature and moisture variations can have a significant impact on pavement performance. Roadbed swelling and frost-heave actions also have major impacts on the load-carrying capacity and service life of asphalt pavements. These should be considered in the pavement design process.
2. **Material properties**—Materials-related design considerations include: strength of pavement layers, resilient modulus of subgrade and base layers, moisture coefficient of base layers, thickness of base layers, swell rate, maximum swelling potential, probability of swelling, frost heave rate, serviceability loss from frost heave, and probability of frost heave. Other materials-related issues, such as asphalt cement softening and stripping, should also be considered (as discussed in Chapter 3).
3. **Performance criteria—**The performance criteria for the pavement structure are established at the beginning of the design process. In the *AASHTO 1993 Design Guide* (AASHTO 1993), performance criteria are established in terms of pavement serviceability, whereas in the *Mechanistic-Empirical Pavement Design Guide* (MEPDG), performance criteria are defined in terms of acceptable levels of rutting, fatigue cracking, thermal cracking, and IRI (AASHTO 2015).
4. **Drainage**—As discussed in Section 4.3, subsurface drainage is one of the critical parameters that governs the long-term performance of pavement structures. The design engineer should consider site-specific conditions and provide appropriate means for excess moisture to drain freely from the pavement.

5. **Type and thickness of asphalt concrete surface layer**—This is dependent on the design objectives. The thickness should be the minimum possible without compromising durability and performance requirements. Additional considerations for surface type are provided in Section 4.4.6.

The MEPDG uses an iterative design process that is illustrated in Figure 4.4.

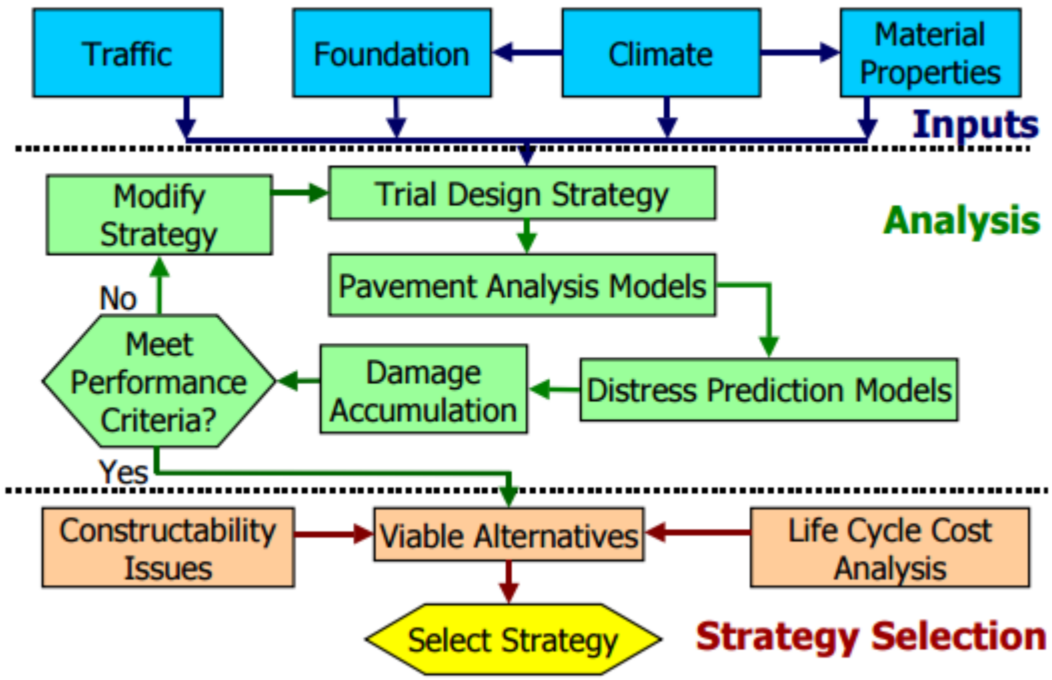

Figure 4.4. Design Process for Flexible Pavements (ARA 2004)

More information on these pavement design procedures is found in AASHTO (1993), NCHRP (2004), and AASHTO (2015).

4.4.5. Specific Design Considerations for Composite Pavements

The main design considerations for composite pavements (asphalt concrete over PCC pavement) are similar to the ones described in Section 4.4.4. The AASHTOWare Pavement ME design procedure for asphalt overlay of jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavements (CRCP) is the most comprehensive method available for overlay design. By using appropriate design inputs, the overlay design procedure can be adapted for new composite pavement structures. The design considerations specific to composite pavement systems involve the following:

- Characterization of the layer properties of the existing concrete layer (if the pavement being designed is an overlay).

- Characterization of the moisture sensitivity of the existing asphalt pavement surface using Modified Lottman (AASHTO T283) (or some other laboratory test method that involves moisture conditioning of asphalt pavement samples) to determine if overlay removal or an adjustment to structural design (e.g., thicker overlay) is required.
- Design of the underlying concrete pavement layer (for new asphalt over concrete composite pavement): pavement type (JPCP or CRCP), thickness, joint load transfer, joint design, and reinforcement design (for CRCP). The base layer and subbase layer designs for new composite pavement designs are similar to those for new JPCP or CRCP designs.
- Controlling reflection cracking and permanent deformation in the asphalt surface layer. Different treatment methods are available to control the development of reflection cracking. Some of the commonly used treatment options include: sealing of cracks in the underlying pavement prior to placement of asphalt overlay; sawing and sealing joints in the asphalt overlay above the joints in the underlying concrete pavement; use of paving fabric, stress-absorbing membrane interlayer (SAMI), or a chip seal interlayer between the existing pavement and the new asphalt surface layer. A review of the various treatment options available for mitigating reflection cracking has been summarized by Dhakal, Elseifi, and Zhang (2016).

Additional guidelines on the design and construction of new composite pavement systems is provided by Rao et al. (2013).

4.4.6. Surface Type Considerations

The surface course of a pavement typically consists of the highest quality materials and provides important surface characteristics such as drainage, friction, noise control, and smoothness. The surface layer is also a barrier to the entry of moisture into the underlying pavement layers. Various types of asphalt surface layers may be selected to achieve specific functional or structural design objectives, including the following:

- **Dense-graded asphalt concrete**—This is the most common surface type used in the U.S. A properly designed, dense-graded mixture is relatively impermeable. They are generally classified as either fine- or coarse-graded, with fine-graded mixtures containing more fines and sand content than coarse-graded mixtures.
- **Stone-mastic asphalt (SMA)**—SMA is a gap-graded asphalt mixture designed to improve rutting resistance and durability by using stone-on-stone contact. Compared to dense-graded asphalt, SMA requires more drainable aggregates, higher-asphalt content, and modified asphalt binders and fibers. Typical SMA and dense-graded asphalt aggregate gradations are shown in Figure 4.5 (Pavement Interactive).
- **Open-graded asphalt surface layers for noise, draining, splash/spray, and friction**—Open-graded surfaces are particularly beneficial in helping transmit stormwater below the surface of the permeable pavement to the roadway shoulder which reduces rate of runoff and peak flow stormwater discharge (Grant et al. 2003).

- **High-friction surfacing such as chip seals or microsurfacing**—These are commonly used as pavement preservation treatments.

Use of rubber-modified or polymer-modified asphalt concrete surface layers provides improved resistance to reflection cracking and top-down cracking. Use of stress-absorbing membrane interlayers can also be helpful in limiting reflection cracking (Van Dam et al. 2015).

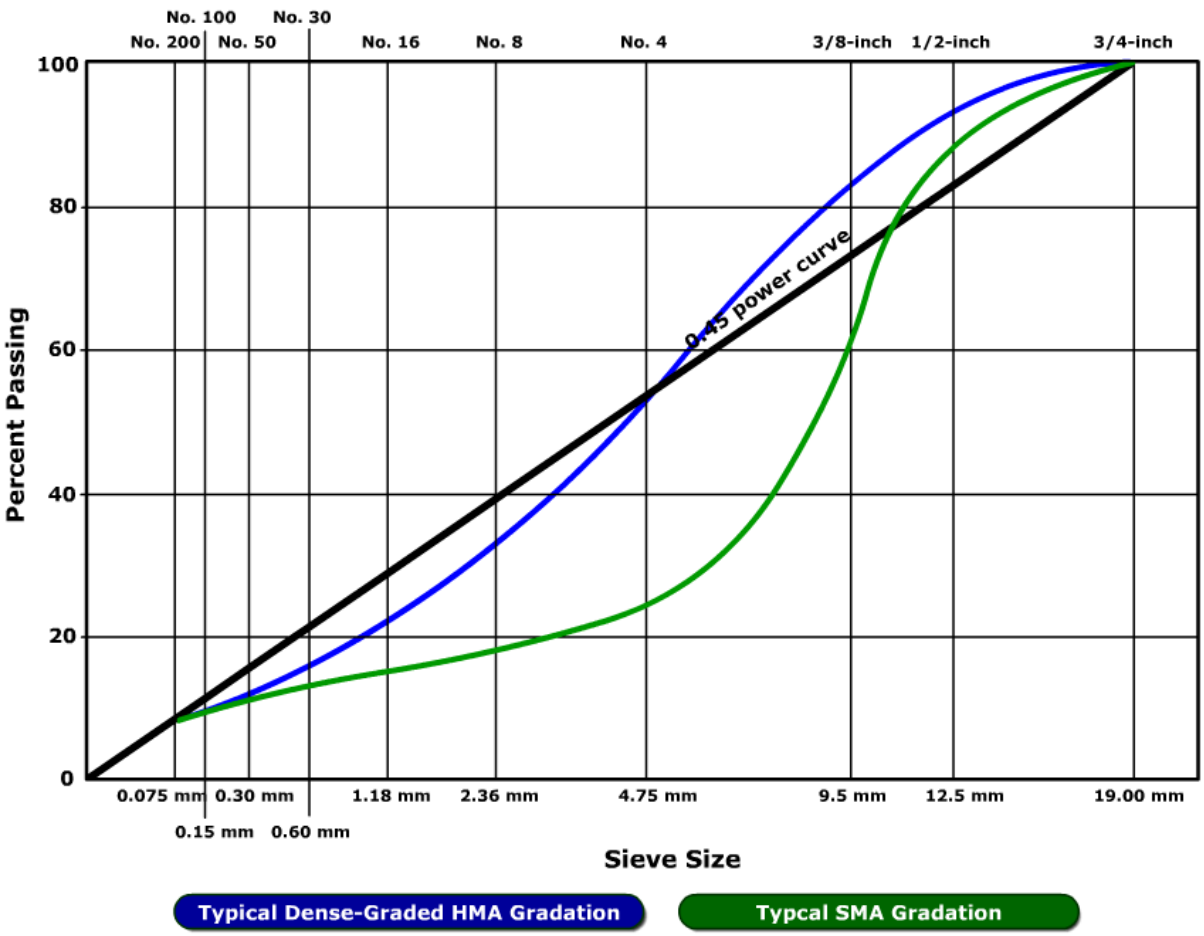

Figure 4.5. Typical SMA and Dense-Graded Asphalt Aggregate Gradations (Source: Pavement Interactive)

4.4.7. Shoulder Design Considerations

The shoulder is the portion of the roadway contiguous with the travel lanes for accommodating stopped vehicles for emergency use or maintenance vehicles. It also provides lateral support for the base and surface layers. The following are general design considerations for shoulders (FHWA 1990):

- Shoulders should be structurally capable of withstanding wheel loads from encroaching truck traffic.
- Shoulder drainage should be integrated with the overall pavement subsurface drainage design.
- Avoid aggregate base courses with more than 6 percent fines to prevent issues such as pumping, clogging of drains, and other base instability issues.
- The shoulder cross slope should be at least 1 percent more than the mainline pavement section cross slope on tangent sections to help with drainage flow. The width, cross slope and other geometric design considerations for highway shoulders are summarized in the AASHTO Green Book (AASHTO 2011).
- Paved shoulders should be visibly distinguished from mainline pavement to discourage the use of the shoulder as a travel lane. This is generally accomplished by pavement marking and possibly by differences in surface texture.
- Treatments such as grooved shoulders can affect surface drainage and such treatments should be offset from the longitudinal lane/shoulder joint to facilitate sealing and minimize moisture infiltration from the surface.
- Use of full-width pavement shoulders is desirable; however, this option may not be feasible on all projects due to the additional cost involved.
- There are three common types of flexible shoulders: (a) bituminous surface-treated shoulders: aggregate shoulders on which asphalt cement and aggregate chips have been applied and rolled, (b) bituminous aggregate shoulder: bituminous mat on top of aggregate base course, and (c) full-depth asphalt shoulders: asphalt mixtures placed on prepared subgrade.
- For new composite pavement systems, concrete shoulders, if used, should be tied to the mainline pavement with properly spaced and sized tiebars. The base layers used for shoulders is generally the same as that used under the mainline pavement, especially on high-volume roadways. Appropriate joint design and reinforcement detailing should be used depending on the type of mainline pavement and other site-specific conditions.
- For new composite pavement systems, the use of widened slabs may be used to reduce edge stresses. In this situation, the outside slab is paved 4 to 4.2 m (13 to 14 ft) wide but the traffic lane is maintained at 3.7 m (12 ft).
- The potential use of the shoulder to serve as a temporary or permanent traffic lane in the future should be considered.

Additional details on design considerations for paved shoulders are available in the FHWA Technical Advisory on Paved Shoulders (FHWA 1990).

4.5. Freeze-Thaw Considerations

It is important to consider the impacts of freezing and thawing temperatures (where applicable) on pavement performance during the pavement design phase. Although the modulus of asphalt bound materials is dependent on temperature (and rate of loading), this section specifically addresses the impacts of freezing and thawing in unbound aggregate layers and subgrade soils.

Freezing temperatures can result in a significant (albeit temporary) increase (20 to 120 times greater than normal conditions) in the resilient modulus of unbound aggregate materials (Christopher, Schwartz, and Boudreau 2006). The formation of ice lenses (described in Section 3.3) can result in heaving conditions, while trapped water during spring thaw can significantly reduce the resilient modulus (and bearing capacity) of unbound aggregate layers and subgrade soils.

Table 4.6 identifies typical frost-susceptible soils based on their Unified Soil Classification. Clean, free draining sands, gravels, crushed rock, and similar granular materials have little to no frost action during normal freezing conditions (Christopher, Schwartz, and Boudreau 2006). The void space between coarse aggregate particles is of sufficient size to allow water to freeze without the buildup of ice lenses. Silty soils are highly susceptible to freeze-thaw conditions due to their relatively small voids between particles, high capillary potential, and relatively low permeability (Christopher, Schwartz, and Boudreau 2006).

Table 4.6. Frost Susceptibility Classification of Soils (Adapted from ARA 2004)

Soil Type	Unified Soil Classification System	% Passing No. 200 Sieve	Degree of Frost Susceptibility
Gravelly soils	GC, GP, GC-GM, GP-GM	3 – 10	Negligible to low
	GM, GC-GM, GP-GM	10 – 20	Low to medium
	GM-GC	> 20	High
Sands	SW, SP, SM, SW-SM, SP-SM	3 – 15	Low to medium
	SM, SC	> 15	High
Clays	CL, CH (PI > 12)[1]	NA	High
	CL, CL-ML (PI < 12)	NA	Very high
Silts	SM	> 15	Very high
	ML-MH	NA	Very high
Varied clays and other fine grained, banded sediments	CL, ML, SM, CH	NA	Very high

[1] Plasticity Index

4.5.1. Heaving Potential

As discussed in the previous section, three key elements contribute to frost heave: moisture, a frost susceptible soil, and subfreezing temperatures. If the three conditions occur uniformly, then the resulting heaving will be uniform; otherwise, differential heaving will occur and this can result in pavement cracking and roughness. Figure 4.6 provides a chart illustrating the heave potential of different soils based on their Unified Soil Classification.

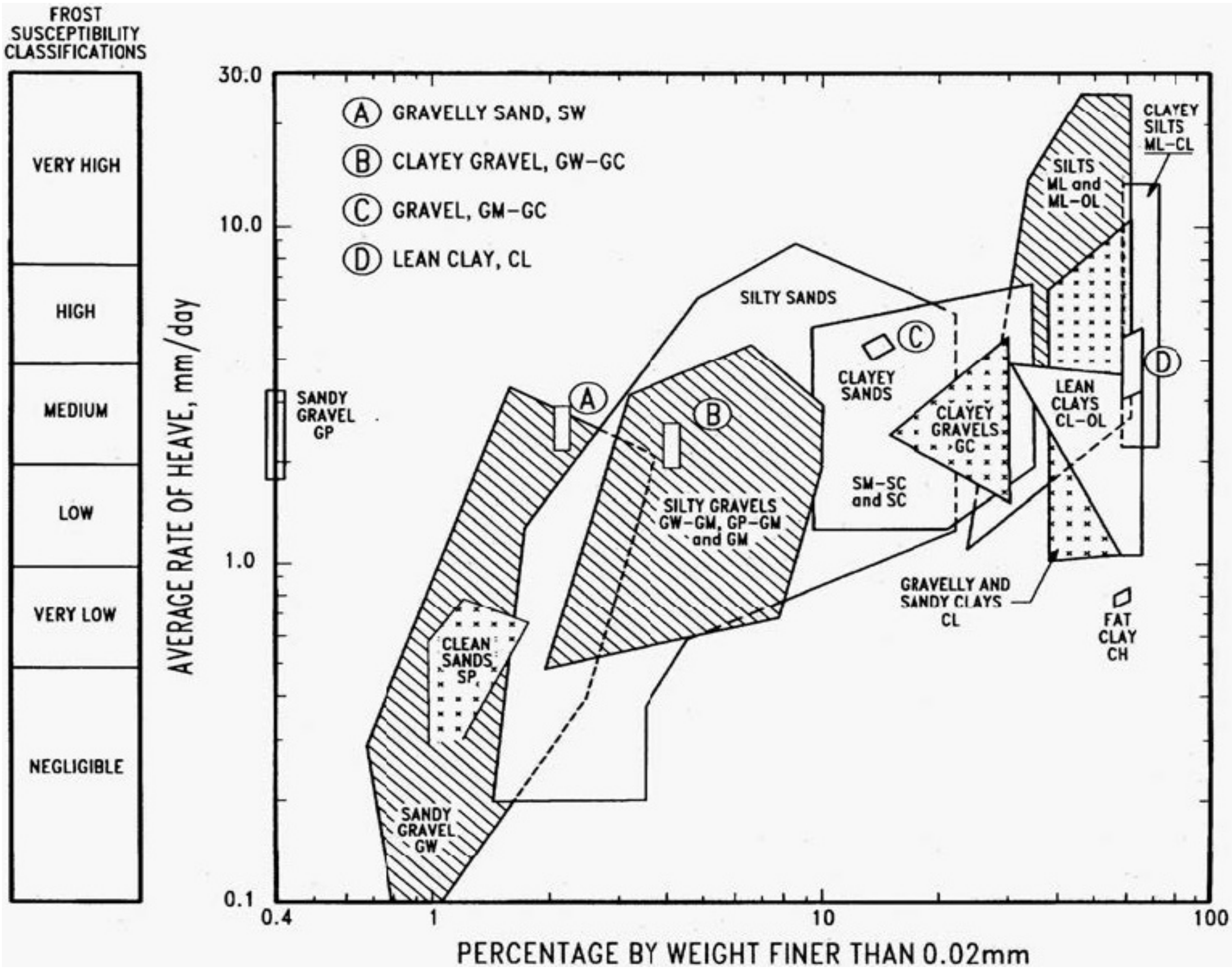

Figure 4.6. Frost Heave Potential as a Function of Grain Size/Soil Type (Kaplar 1974)

Areas that are more susceptible to differential heaving include the following conditions (WSDOT 1995):

- Subgrade changes from clean non-frost-susceptible (NFS) materials to silty frost-susceptible materials.
- Abrupt transitions from cut to fill in areas where the water table is close to the surface.
- Excavation exposes water-bearing strata.
- Locations with drains, culverts, and other drainage structures frequently result in differential heaving due to differences in backfill material compaction and other thermal incompatibility issues.

Other factors affecting the degree of heaving include the following (WSDOT 1995):

- Rate of heat removal.

- Temperature gradient.
- Soil permeability.
- Depth of water table.
- Soil type and condition.

4.5.2. Methods for Mitigating Damage

The following are some of the effective methods for mitigating damage due to freeze-thaw conditions (Christopher, Schwartz, and Boudreau 2006):

- Remove the frost-susceptible soil and replace it with a non-frost-susceptible material to the depth of expected freeze.
- Place and compact non-frost-susceptible materials over the existing subgrade soils. The depth of placement should be sufficient to prevent freezing of the subgrade soils.
- Remove isolated pockets of frost-susceptible soils to eliminate differential heaving.
- Stabilize the subgrade soil (discussed in Chapter 6) through mechanical methods (e.g., adding more gravel, geosynthetics, lightweight fill), admixtures (e.g., portland cement, lime, chemicals), water proofers (e.g., asphalt, geomembranes), or moisture removal (e.g., deep drains, capillary barrier).
- Increase the structural layer thickness to account for lower subgrade modulus during spring thaw.

4.6. Summary

There are three primary design approaches for minimizing moisture damage in asphalt-surfaced pavement systems: prevent moisture from entering the pavement system, use materials and design procedures that are insensitive to moisture effects, and quickly drain the excess moisture that enters the pavement system using a variety of drainage features. This chapter provides information on key considerations for roadway geometric design, subsurface drainage, and pavement design that help in minimizing moisture damage in flexible and asphalt over concrete composite pavement systems.

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CHAPTER 5. MATERIAL TYPE AND SELECTION

5.1. Introduction

In addition to designing the pavement section and drainage system to address the presence of water in the pavement structure, it is important to select materials that are insensitive to moisture or that help minimize its damaging effects. This chapter summarizes material characteristics for each pavement layer, geosynthetic material, and material used in drainage systems.

5.2. Pavement Structure

The typical materials used in asphalt and composite pavements include in situ or treated subgrade soils, unbound aggregate or treated base, concrete pavement, and asphalt pavement. In general, granular materials with low fines content, cement-stabilized and lean concrete base, and asphalt-stabilized base materials are relatively insensitive to moisture damage (Christopher, Schwartz, and Boudreau 2006).

5.2.1. Base Layers

The primary purpose of the base layer for asphalt pavements is to provide a structural layer to support the anticipated traffic loads. The asphalt pavement base layer should provide adequate stiffness, resist fatigue damage, and be of sufficient thickness to distribute the load through the base layer thickness (Christopher, Schwartz, and Boudreau 2006). For composite pavements, in addition to providing structural support, the base layer also provides support during placement of the concrete layer (Christopher, Schwartz, and Boudreau 2006). The following summarizes more commonly used base types:

- **Unbound aggregate base**—Typically consists of dense-graded aggregate that is crushed, durable, and erosion resistant.
- **Aggregate separator layer**—For weaker subgrade soils (e.g., silts, saturated cohesive soils), a geotextile can be placed beneath the base layer to minimize the migration of the fine-grained soil into the base. The aggregate separator layer should provide a stable working platform during placement of the permeable base and consist of durable, crushed, angular material. Additional information on applicable geotextile materials is discussed in Section 5.3.
- **Asphalt- or cement-treated**—Asphalt- and cement-treated bases are typically stronger, stiffer, more durable, and more resistant to moisture than comparable, non-stabilized aggregate materials.
- **Asphalt- or cement-treated permeable base**—The aggregate for treated permeable-treated bases should consist of crushed material to provide stability during placement. Treated permeable bases utilize open-graded aggregate stabilized with asphalt cement or portland cement.

Table 5.1 summarizes properties and recommended criteria for the various base layer materials.

Table 5.1. Base Layer Material Recommendations (FHWA 2002; ARA 2004; Chatti et al. 2005; Christopher, Schwartz, and Boudreau 2006)

Base Type	Gradation	Fractured Faces	L.A. Abrasion[a]	Soundness[b]	Permeability	Binder/Mix
Unbound Aggregate	No or minimal fine material passing the No. 200 sieve	Preferably 98 %, two fractured faces	< 45%	< 12 % (sodium sulfate) < 18 % (magnesium sulfate)	NA	NA
Aggregate Separator Layer	Dense-graded aggregate (typical) < 12 %, by weight, passing No. 200 sieve Material passing No. 40 sieve should be nonplastic[c]	Preferably 98 %, two fractured faces for material retained on No. 4 sieve	< 50%	< 12 % (sodium sulfate) < 18 % (magnesium sulfate)	< 4.58 m (15 ft/day)	NA
Asphalt-Treated Base	Varies by agency	Preferably 98 %, two fractured faces	< 45%	< 12 % (sodium sulfate) < 18 % (magnesium sulfate)	NA	1 grade stiffer than surface course Binder content to provide well-coated aggregate, 2.5 % by weight (minimum)[d] Anti-stripping[e]
Asphalt-Treated Permeable Base	0 % passing the No. 200 sieve Material passing No. 40 sieve should be nonplastic[c] AASHTO 57 or 67 gradation (typical)	Preferably 98 %, two fractured faces	< 45%	< 12 % (sodium sulfate) < 18 % (magnesium sulfate)	> 305 m (1,000 ft/day)	1 grade stiffer than surface course Binder content 2.5 to 3 % by weight (minimum)[d] Anti-stripping[e]
Cement-Treated Base	Varies by agency	Preferably 98 %, two fractured faces	< 45%	< 12 % (sodium sulfate) < 18 % (magnesium sulfate)	NA	Portland cement[f] 131 to 169 kg/m^3 (220 to 285 lb/yd^3) Compressive strength: 217 to 434 kg/m^2 (400 to 800 lb/yd^2) (7 day) Water-cement ratio: 0.3 to 0.5 Slump: 25 to 76 mm (1 to 3 in.)
Cement-Treated Permeable Base	0 % passing the No. 200 sieve Material passing No. 40 sieve should be nonplastic	Preferably 98 %, two fractured faces	< 45%	< 12 % (sodium sulfate) < 18 % (magnesium sulfate)	> 305 m (1000 ft/day)	Portland cement[f] 131 to 169 kg/m^3 (220 to 285 lb/yd^3) Water-cement ratio: 0.3 to 0.5 Slump: 25 to 76 mm (1 to 3 in.)

[a] AASHTO T 96, Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.
[b] AASHTO T 104, Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate.
[c] AASHTO T 90, Determining the Plastic Limit and Plasticity Index of Soils.
[d] AASHTO T 195, Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures.
[e] AASHTO T 283, Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage.
[f] AASHTO M 85, Standard Specification for Portland Cement.

5.2.2. Asphalt Mixture Properties

Test methods for determining the moisture sensitivity of asphalt mixtures are grouped into three categories (1) tests on asphalt mix components and component compatibility, (2) tests on the loose mix, and (3) tests on the compacted mix (Santucci 2010). Test procedures that fall within each of these three categories are described in the following sections.

5.2.2.1. Mix Components and Component Compatibility

Tests for evaluating the mix component and component compatibility include the sand equivalent test and the methylene blue test (see Table 5.2).

Table 5.2. Common Asphalt Mix Aggregate Tests for Accessing Moisture Susceptibility (Santucci 2010; TRB 2015)

Property	Standard	Typical Specification
Sand Equivalent	AASHTO T 176, Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent	40 – 50 (minimum)[1]
Methylene Blue Value	AASHTO T 330, Qualitative Detection of Harmful Clays of the Smectite Group in Aggregates Using Methylene Blue	High value may be associated with a high amount of harmful material or more active clay minerals[2]

[1] AASHTO M 223, Superpave Volumetric Mix Design.
[2] Prowell, Zhang, and Brown 2005.

One of the primary concerns in aggregate selection is ensuring that there will be sufficient adhesion between the aggregate particles and the asphalt binder. Strong adhesion of the asphalt binder to the aggregate particles will result in a decreased potential for asphalt mix moisture damage. Methods for increasing adhesion include the following (Kandhal and Richards 2001):

- Thoroughly dry the aggregate prior to the addition of the asphalt binder.
- Increase the aggregate drying temperature to remove water or water vapor.
- Use weathered aggregate.
- Remove dust coatings.
- Use aggregates with increased angularity, roughness, and absorption, and with decreased permeability.
- Use aggregates with improved resistance to thermal, freeze-thaw, chemical or other disintegration mechanisms.

5.2.2.2. Loose Mix

Loose mix testing includes the evaluation of asphalt-coated aggregates in the presence of water. While loose mix tests typically require shorter testing times, lower testing costs, and simpler equipment and test procedures, they are unable to quantify the effect of traffic, mix properties, and the environment (Santucci 2010). The more common loose mix test procedures are shown in Table 5.3.

Table 5.3. Common Tests for Evaluating Loose and Compacted Mix Susceptibility to Moisture Damage (Santucci 2010; TRB 2015)

Standard	Description	Loose or Compacted	Conditioning	Typical Specification
AASHTO T 165	Effect of Water on Compressive Strength of Compacted Bituminous Mixtures (Immersion Compression)	Compacted	24 h @ 60°C	Strength ratio ~ 1.0
AASHTO T 283	Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage (Modified Lottman)	Loose and Compacted	16 h @ 60°C (loose) 16 h at -18°C (compacted) 24 h @ 60°C (compacted) 2 h @ 25°C (compacted)	≥ 80 %
AASHTO T 324	Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)	Loose and Compacted	4 h @ 135°C (loose) 30 min @ test temperature (compacted)	≤ 13 mm (0.5 in.) rut depth at 10,000 passes[1]
ASTM D3625	Effect of Water on Bituminous-Coated Aggregate Using Boiling Water	Loose	Boiling H2O 10 min	Visual check for stripping
ASTM D4867	Effect of Moisture on Asphalt Concrete Paving Mixtures (Root Tunnicliff)	Compacted	15+ h @ -18°C 24 h @ 60°C 1 h @ 25°C	≥ 80 %

[1] Based on Colorado DOT study, good performing pavements had stripping inflection points greater than 10,000 passes (Aschenbrener 1995). Texas DOT requires ≤ 13 mm (0.5 in.) rut depth after 10,000 passes for PG 64 or lower, 15,000 passes for PG 70, and 20,000 passes for PG 76 or higher (TxDOT 2014).

5.2.2.3. Compacted Mix

Compacted mix test methods are conducted on laboratory compacted specimens, field cores, or slabs. Many of the compacted mix test methods compare the mix strength before and after exposure to temperature and freeze-thaw cycles. Compared to loose mix tests, compacted mix tests produced quantitative results considering the impacts of traffic, mix properties, and the environment (Santucci 2010). Common test methods for compacted mixtures are presented in Table 5.3.

The following are additional recommendations for decreasing compacted mix susceptibility to moisture damage (Kandhal and Richards 2001):

- Decrease the mix air void level and permeability.
- Increase the asphalt film thickness.
- Use effective antistripping additive.

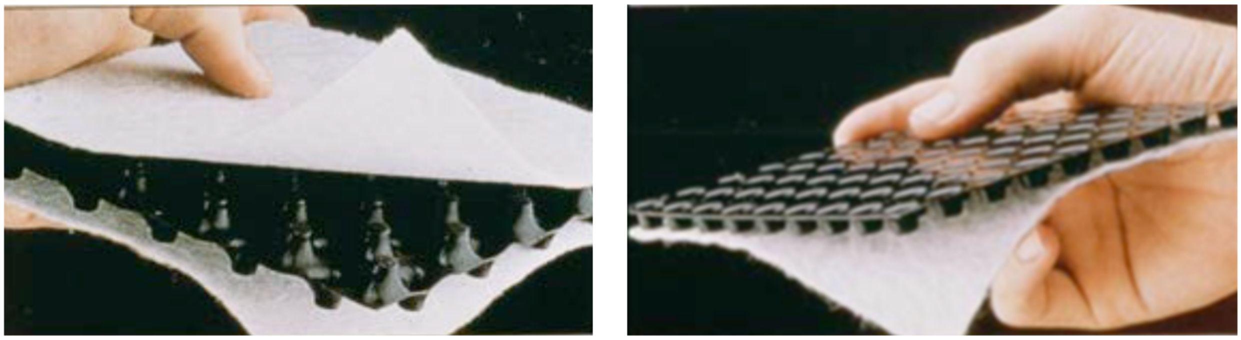
- **Liquid additives**—Typical dosage ranges from 0.5 to 1.0 percent by weight of asphalt cement and is dependent on the type of aggregate.
- **Hydrated lime and quicklime**—Typical dosage includes 0.5 to 2.0 percent hydrated lime by weight of aggregate.

5.3. Geosynthetics

Geosynthetics are used in a wide variety of engineering applications and include a broad category of products (e.g., geotextiles, geocomposites, geomembranes, geogrids, geofoam). Pavement engineering applications include subgrade separators, subgrade soil stabilization, and drainage systems. Geosynthetic products used in the pavement structure include geotextiles and drainage geocomposites (GMA 2015):

- **Geotextiles**—There are two primary types of geotextiles: nonwoven and woven. Figure 5.1 illustrates a variety of geotextile products (nonwoven on the left, woven on the right). Nonwoven geotextiles are manufactured from staple fibers or continuous filaments to form a felt-like "web," and are typically used for separator layers, subsurface drainage, and erosion control applications. Woven geotextiles are made from weaving monofilament, multifilament, or slit film yarns, and are generally used for sediment control (GMA 2015).
- **Drainage geocomposites—**Drainage geocomposites consist of a blanket drain or preformed core wrapped with a geotextile filter (Figure 5.2). Drainage geocomposites are typically used in edge drain applications.

Figure 5.1. Geotextile Examples

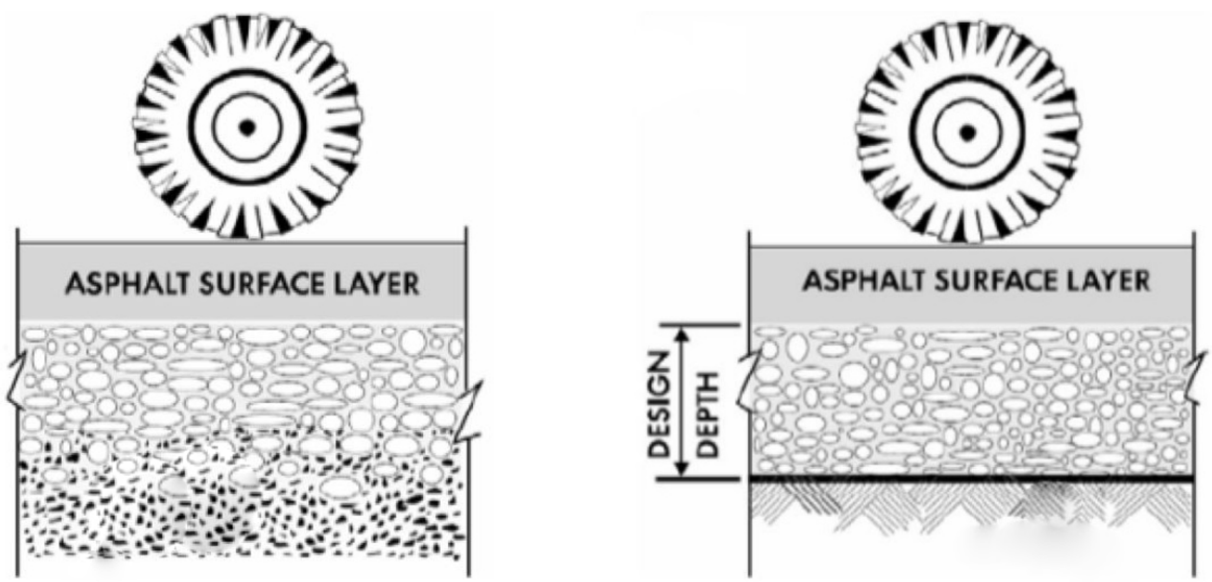


a. Double-sided b. Single-sided

Figure 5.2. Drainage Geocomposite Examples (GMA 2015)

5.3.1. Geotextile Separator Layer

Geotextiles used as a separator layer may consist of either woven or nonwoven materials and should meet filtration and construction survivability requirements. A geotextile may be placed between the base layer and subgrade soil to minimize the migration of fine-grained soil (Figure 5.3).



a. Pavement without geotextile. b. Pavement with geotextile.

Figure 5.3. Illustration of Geotextile Separation Function (Zornberg and Thompson 2012)

Geotextile separator layer properties are summarized in Table 5.4.

Table 5.4. Geotextile Separator Layer Properties (AASHTO M 288-15)

		Requirement		
Property	**Standard**	**Cleared of Obstacles[1]**	**Cleared of Larger Obstacles[2]**	**Minimal Site Preparation[3]**
Construction Equipment Ground Pressure				
Low (≤ 25 kPa [3.6 lb/in^2])	NA	Class 3	Class 2	Class 1
Medium (>25 kPa ≤ 50 kPa [> 3.6 lb/in^2 ≤ 7.3 lb/in^2])	NA	Class 2	Class 1	Class 1+4
High (> 50 kPa [7.3 lb/in^2])	NA	Class 1	Class 1+4	Not recommended
Grab Strength, lb	ASTM D4632	See Table 5.5 based on selected class		
Sewn Seam Strength, lb	ASTM D4632	See Table 5.5 based on selected class		
Tear Strength, lb	ASTM D4533	See Table 5.5 based on selected class		
Puncture Strength, lb	ASTM D6241	See Table 5.5 based on selected class		
Permittivity, sec^{-1}	ASTM D4491	0.02		
Maximum Apparent Opening Size	ASTM D4751	0.43 mm (0.017 in.)		
Ultraviolet Degradation @ 500 hours exposure, % retained	ASTM D4355	50		

[1] All obstacles have been cleared except grass, weeds, leaves, and fine wood debris; surface is smooth and level, no more than 457 mm (18 in.) high humps or depressions; or a smooth working table has been placed.

[2] Small to moderate-sized tree limbs and rocks have been removed; tree trunks and stumps have been removed or covered with a smooth working table; and surface is smooth and level, no more than 457 mm (18 in.) high humps or depressions.

[3] Trees may be felled, delimbed, and left in place; stumps are cut to project no more than 152 mm (6 in.) above subgrade; items are removed only if they distort the finished road surface.

[4] Class has not been specified by AASHTO, requires additional Agency specification.

5.3.2. Drainage Systems

Drainage systems typically consist of an aggregate trench, geotextile, drain pipe, and outlet. As discussed in Chapter 4, each component of the drainage system should have the hydraulic capacity to handle the movement of water from the base material to the outlet pipes or daylighted shoulders. The following summarizes the material properties of the drainage system components (FHWA 2002):

- **Trench backfill**—Trench backfill material should be stable with sufficient permeability values to ensure the flow of water.
- **Drain pipe**—The following pipe materials are commonly used in drainage systems.
  - Corrugated polyethylene (CPE) pipe should be in accordance with AASHTO M 252, *Standard Specification for Corrugated Polyethylene Drainage Pipe*.
  - Polyvinyl chloride (PVC) pipe should be in accordance with AASHTO T 278, *Standard Specification for Class PS46 Poly (Vinyl Chloride) (PVC) Pipe.*

- Smooth wall pipe with corrugations should conform to AASHTO M 304, *Standard Specification for Poly (Vinyl Chloride) (PVC) Profile Wall Drain Pipe and Fittings Based on Controlled Inside Diameter,* ASTM F949, *Standard Specification for Poly (Vinyl Chloride) (PVC) Corrugated Sewer Pipe With a Smooth Interior and Fittings,* or AASHTO M 252.
- Heat-resistant pipe should be used if the drainage trenches will be backfilled with asphalt material. Pipe selection should be based on the ability of the material to withstand the asphalt material placement temperature.

- **Outlet pipe**—The outlet pipe should consist of a non-perforated, high stiffness polyethylene or PVC pipe. The pipe stiffness should be greater than 448 kPa (65 lb/in^2). Plastic pipe meeting ASTM D3034 with a Standard Diameter Ratio (SDR) of 23.5 or ASTM D2665, Schedule 40, are considered appropriate for the outlet pipe.
- **Headwalls**—To minimize damage to the headwall during maintenance operations, cast-in-place or precast concrete headwalls should be used.
- **Geotextile**—When used in a drainage system, the permeability of the geotextile should be several times greater than the permeability of the subgrade soil (FHWA 2002). Table 5.5 provides a summary of geotextile strength properties and Table 5.6 provides a summary of geotextile drainage properties. Material properties for geotextiles used to stabilize the subgrade are shown in Table 5.7.

Table 5.5. Geotextile Strength Properties (AASHTO M 288-15)

Property	Standard	Class 1[1,2,34]	Class 2[2,3,4]	Class 3[2,3,3]
Grab Strength	ASTM D4632	1.4 / 0.9 kN (315 / 202 lbf)	1.1 / 0.7 kN (247 / 157 lbf)	0.8 / 0.5 kN (180 / 112 lbf)
Sewn Seam Strength	ASTM D4632	1.3 / 0.8 kN (283 / 182 lbf)	1.0 / 0.6 kN (223 / 142 lbf)	0.7 / 0.5 kN (162 / 101 lbf)
Tear Strength	ASTM D4533	0.5 / 0.4 kN (112 / 79 lbf)	0.4 / 0.3 kN (90[5] / 56 lbf)	0.3 / 0.2 kN (67 / 40 lbf)
Puncture Strength	ASTM D6241	2.8 / 1.9 kN (618 / 433 lbf)	2.2 / 1.4 kN (495 / 309 lbf)	1.7 / 1.0 kN (371 / 223 lbf)

[1] Class 1 is typically specified for severe or harsh installation conditions where greater potential for geotextile damage exists.
[2] All values based on minimum average roll value (MARV) in the weaker principal direction.
[3] In accordance with ASTM D4632.
[4] Values shown for < 50 % / ≥ 50 % elongation.
[5] The required MARV tear strength for woven monofilament geotextiles is 20.3 kN (56 lbf)

Table 5.6. Drainage Geotextile Properties: Class 2 Geotextiles (AASHTO M 288-15)

Property	Standard	% Soil Passing No. 200 Sieve < 15	15 to 50	> 50
Permittivity, sec^{-1}	ASTM D4491	0.5	0.2	0.1
Maximum Apparent Opening Size	ASTM D4751	0.43 mm (0.017 in.)	0.25 mm (0.010 in.)	0.23 mm (0.009 in.)
Ultraviolet Degradation @ 500 hours exposure, % retained	ASTM D4355	50	50	50

Table 5.7. Stabilization Geotextile Properties (AASHTO M 288-15)

Property	Standard	Requirement
Grab Strength, lb	ASTM D4632	See Table 5.5
Sewn Seam Strength, lb	ASTM D4632	See Table 5.5
Tear Strength, lb	ASTM D4533	See Table 5.5
Puncture Strength, lb	ASTM D6241	See Table 5.5
Permittivity, sec^{-1}	ASTM D4491	0.05
Maximum Apparent Opening Size	ASTM D4751	0.0152 mm (0.0006 in.)
Ultraviolet Degradation @ 500 hours exposure, % retained	ASTM D4355	50

5.4. Summary

The materials used in the pavement structure and drainage systems play an important role in minimizing damage due to the presence of moisture. This includes utilizing strong, durable, and crushed aggregate in pavement layers. For asphalt layers, aggregate materials should be dry, clean, and weathered with increased angularity, roughness, and absorption, and with decreased permeability. When subjected to cold climates, aggregate for asphalt layers should also be resistant to thermal, freeze-thaw, and chemical or other disintegration mechanisms. In addition, asphalt mixtures should be designed and constructed to minimize permeability, provide sufficient asphalt film thickness, and include an effective antistripping additive (as appropriate).

Geosynthetic materials are utilized for subgrade stabilization, separation, and in drainage systems. Depending on the application, the selection of the appropriate geotextile material is key to ensuring both survival during construction and acceptable long-term performance.

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CHAPTER 6. NEW CONSTRUCTION

6.1. Introduction

As with any new facility construction project, the best time to address a potential problem is in the planning or design phase—before the facility is constructed. This is certainly true when considering a potential moisture damage problem in a new pavement construction project. This chapter provides detailed guidelines for the construction of new pavement layers, subsurface drainage systems, and roadway widening to help address potential moisture damage problems in both asphalt concrete and composite pavement structures.

6.2. Pavement Layers

The subgrade soil and other layers of a pavement structure can all be affected by moisture. Consequently, when constructing a pavement in a moisture-prone environment, it is worth considering various techniques to help reduce the moisture susceptibility of these layers. It is also important to emphasize best construction practices for all pavement layers.

6.2.1. Subgrade Soil Treatment Requirements

For most new pavement construction projects, the process of preparing the subgrade soil involves clearing and grubbing the surface to remove all vegetation and organic materials, grading and shaping to meet the target longitudinal and transverse profile requirements, applying water to meet the target soil moisture content, and compacting the material to achieve the density requirement. For some projects, there may be an underlying problem with excess moisture that may not reveal itself as a soft spot until after haul trucks and other heavy construction equipment travel over the subgrade multiple times. This state of high moisture in the subgrade soil can be serious and should not be ignored. If adequate density is not achieved in these areas or other soft spots, it will be difficult to achieve the target densities (and strengths) in the pavement layers above. This, in turn, will result in greater moisture susceptibility as well as reduced pavement performance. Proof rolling is the method normally used to identify weak areas and determine the limits of the problem area. In the proof rolling process, the contractor or inspector observes the surface displacement created by a heavy truck moving along the roadway alignment (Figure 6.1). Any areas where significant displacement is observed are marked and then targeted for further attention, such as over-excavating the weak material and replacing it with a better quality base material.

Figure 6.1. Water Truck Being Used to Proof Roll a Section of Compacted Material to Locate Any Soft Spots

Other methods that have been used to evaluate the subgrade soil conditions—especially when the soft spot or moisture problem may be below the surface—include the use of a Dynamic Cone Penetrometer (ASTM D6951) or an automated pavement deflection device. In the case of the DCP, a steel bar with a hardened cone tip is driven into the soil using a 8-kg (17.6-lb) hammer dropped from a height of 574 mm (22.6 in). After a set number of drops, the penetration is measured/recorded, and the process is continued to a target depth. The identification of the potential problem areas is based on data that show high penetration values. In the case of an automated pavement deflection device (such as a light-weight deflectometer), a load is applied to the soil surface (through some combination of hydraulic and electro-mechanical process) and the vertical displacement of the surface is measured by deflection sensors. The identification of the potential problem areas is based on data that show high vertical displacement values.

In situations where the subgrade soil is of such poor quality that it cannot effectively support the pavement, there are a variety of methods that can be employed to address the problem. These methods will improve the soil's properties in one or more of the following ways: increasing its strength, reducing its moisture susceptibility, protecting it from frost penetration, or creating a better working platform for pavement construction. For purposes of this discussion, these treatments are broken down into three categories, Removal and Replacement, Stabilization Methods, and Dewatering Systems (Christopher, Schwartz, and Boudreau 2006).

6.2.1.1. Removal and Replacement

One option for addressing a poor subgrade soil is to remove and replace a portion of it with a better quality material from somewhere else on the project or using a *select fill* material hauled in from another location. This option is often used because it seems to be the easiest, particularly for local soft spots. However, for large areas, it is not likely to be cost effective, particularly if hauling costs are high. For example, if the problem is the result of frequent high levels of moisture, the preferred method may be the stabilization or dewatering strategies discussed later.

If removal of a poor quality subgrade soil material is required, the excavation is usually carried out using scrapers or shovels (excavators). In a new pavement construction project where cut and fill earthwork is required, scrapers (Figure 6.2) are the standard equipment used to cut material from one location that is above grade and move it to another location that is below grade. Accordingly, if the poor soil can withstand the weight, scrapers—especially those equipped with an elevator system to load the soil into a truck—are probably the ideal equipment for soil removal. In situations where the subgrade soil is too soft to support the weight of the scraper, a tracked excavator (Figure 6.3) may be more appropriate. It should be noted that for whatever the project size, the goal is to remove the soft, weak material to a depth where competent (i.e., dry, firm) materials are found.

Figure 6.2. Scraper Earth Moving Equipment

Figure 6.3. Track-Mounted Excavator

After the soft or defective materials are removed and before the replacement material is hauled in, it is important to inspect the site closely to determine if there are any sources of moisture that may create moisture problems after construction, such as an underground spring or perched water table. Obviously, this is not the best time to discover these moisture sources because it will result in construction delays as a solution is identified and implemented. However, if it is not addressed, it could lead to a more costly intervention in the future.

As previously stated, the replacement material may come from another part of the project where material had to be excavated to get down to grade or it may be a select fill material brought in from another source (ideally a nearby one). The material is usually delivered to the site by some type of haul truck, such as an end-dump, bottom-dump, side-dump, or articulated-dump truck. Scrapers, bulldozers, or graders are then used to spread the material and bring it up to grade. If the depth of material to be added is significant (over 0.3 m [1 ft]), the final grade will probably need to be achieved in a layered process, with each layer being compacted to a specified level associated with the material. The type of compaction equipment that should be used for a given project is dependent on the type of replacement fill material. Table 6.1 provides a list of recommended equipment based upon the type of material (Rollings and Rollings 1996).

Table 6.1. Recommended Types of Compaction Equipment for Different Soil/Fill Materials (After Rollings and Rollings 1996)

Soil	First Choice	Second Choice	Comment
Rock fill	Vibratory	Pneumatic	--
Plastic soils, CH, MH (A-7, A-5)	Sheepsfoot or Padfoot	Pneumatic	Thin lifts usually needed
Low-plasticity soils, CL, ML (A-6, A-4)	Sheepsfoot or Padfoot	Pneumatic, vibratory	Moisture control often critical for silty soils
Plastic sands and gravels, GC, SC (A-2-6, A-2-7)	Vibratory, Pneumatic	Padfoot	--
Silty sands and gravels, SM, GM (A-3, A-2-4, A-2-5)	Vibratory	Pneumatic, padfoot	Moisture control often critical
Clean sands, SW, SP (A-1-b)	Vibratory	Impact, pneumatic	--
Clean gravels, GW, GP (A-1-a)	Vibratory	Pneumatic, impact, grid	Grid useful for oversize particles

It should be noted that moisture control is an important part of the compaction process. If the material is too wet, it should be allowed to dry to a level near optimum before compaction is attempted. In contrast, if the material is too dry, water trucks should be used to bring the material to a level near optimum, so that the target density and desired soil support can be achieved.

6.2.1.2. Stabilization Methods

Section 4.4.2 identified several methods of stabilizing a subgrade soil that has been determined to be too weak or too susceptible to moisture. The methods fell under one of two categories: mechanical stabilization and chemical stabilization. Following is a basic description of the construction process and key construction considerations for each:

1. **Mechanical stabilization through addition of gravel**—The placement and compaction of a gravel layer for mechanical stabilization is essentially the same as that described for subgrade removal and replacement in Section 6.2.1.1. The gravel may be added as the replacement layer after the poor quality (silt or clay) subgrade soil material is removed, or it may be added directly on top (Christopher, Schwartz, and Boudreau 2006). Some of the key construction considerations associated with this process include:
   - Placing the material in a manner that limits the amount of subgrade soil infiltration.
   - Achieving a stable working platform with a minimal thickness of material.
   - Achieving stability in material that may not be uniformly graded.

2. **Mechanical stabilization through blending**—The preferred method for blending two different soil materials to overcome deficiencies in grading is to feed the materials into two separate aggregate bins, convey them at pre-proportioned rates into a pugmill mixer, and then load, haul, place, and compact the blended mixture in a manner best suited for the material (Rollings and Rollings 1996). To minimize the haul cost, blending should take place on site. An alternate method for blending may be used if the goal is simply to blend gravel (or recycled pavement material) directly into the subgrade soil. The gravel material is hauled to the site, dumped on the surface, and then worked into the soil using a single-shaft rotary mixer, a grader with a scarifier attachment, or a tractor with a disc harrow. No matter what approach is used, multiple passes will be required to achieve adequate mixing. After mixing, the material is graded and then compacted in a manner best suited for the blended material.
3. **Mechanical stabilization through the use of geosynthetic materials**—The two primary types of geosynthetic materials used to help stabilize a weak subgrade soil are geotextile fabrics and geogrids. As stated in Section 5.3., fabrics are better suited for maintaining separation between two layers, allowing for the passage of moisture into a drainage layer (filter fabrics), and serving as an impermeable layer (treated fabrics) that can be used in a subsurface drainage system. Geogrids are best suited for reinforcement. These materials are typically delivered to the site in wrapped, 6-ft wide rolls and must be kept protected from UV radiation as well as from physical damage. After the subgrade soil is graded and compacted using conventional techniques, the rolls are unwrapped, unrolled and overlapped in parallel strips over the subgrade, and the seams are sewn to enable the transmission of tensile stresses. After placement, the geosynthetic material is covered with the next layer of soil, pavement, or drainage layer material and then compacted according to the requirements specified for the geosynthetic material (Rollings and Rollings 1996). Typically, an appropriately sized pneumatic roller is used to both compact and pre-stress the geosynthetic layer. Problems typically encountered during construction are associated with these site conditions (Richardson and Wyant, 1987):
   - Fill placement or compaction techniques damage the geotextile.
   - Installation loads are greater than design loads, leading to failure during construction.
   - Construction environment leads to a significant reduction in assumed fabric properties, causing failure of the completed project.
   - Field seaming or overlap of the geotextile fails to fully develop desired fabric mechanical properties.
   - Instabilities during various construction phases may render a design inadequate even though the final profile would have been stable.
4. **Mechanical stabilization through the use of lightweight fill materials**—The placement and compaction of a lightweight fill material are essentially the same as that described in Section 6.2.1.1. The lightweight material may be added as the replacement layer after the poor quality subgrade soil material is removed, or it may be added directly on top of the subgrade soil material. Recall, however, that the primary reason for using the lightweight material is to help reduce the increased overburden and higher consolidation potential associated with a heavier gravel material. As with the gravel

material, the following are the key construction considerations associated with this process:

- Placing the material in a manner that limits the amount of subgrade soil infiltration.
- Achieving a stable working platform with only a thin layer of fill material.
- Achieving stability in material that may not be uniformly graded.

5. **Admixture stabilization using portland cement**— The basic construction steps for using cement to stabilize a poor quality subgrade soil in place include spreading the cement, mixing the cement with the soil, compacting, final grading, and curing (Rollings and Rollings 1996). The spreading process involves the use of mechanical spreaders that are calibrated to distribute the cement to achieve the design application rate. For mixing, the most common method involves the use of either a transverse rotary mixer (Figure 6.4) or a windrow-type traveling mixer. It is recommended that either sheepsfoot or pad-foot rollers be used for initial compaction, followed by either pneumatic-tire or steel-wheel vibratory rollers. To achieve a better bond with a subsequent layer, the surface should be roughened with a hydraulic scratcher or spike-tooth harrow. Like most new pavement construction projects, final grading is carried out using a grader immediately after compaction. Curing will require 3 to 7 days under moist conditions. Typically, moist conditions are maintained by placing plastic sheeting. However, if the surface will be trafficked, then a bituminous surface seal or periodic watering will be required. Some of the key construction considerations include:

Figure 6.4. Single-Shaft, Transverse Rotary Mixer Used to Mix Cement into the Soil as Part of a Soil Stabilization Process

- Moisture and temperature control—The highest strengths are achieved when the material is kept in a moist condition and temperatures do not drop below 40 °F.
- Cement uniformity—It is difficult to achieve uniform distribution of cement in the field, so the design cement content is often increased by 1 or 2 percent to help ensure an adequate quantity throughout.
- Compaction window—Because cement hydration begins almost immediately after mixing, compaction should begin within 1 hour after mixing and be completed within 2 hours. These times will be shorter on hot days. Retarders may be used to help increase the compaction window, but they may also affect the curing time.
- Microcracking—After cement stabilization, some subgrade soil materials are more susceptible to shrinkage cracking that could produce reflection cracking in the asphalt concrete surface layer. In these cases, it may be necessary to use a heavy, vibratory roller near the end of the curing process to create smaller (micro) cracks in the stabilized layer so that it will not induce reflection cracking in the asphalt surface.

6. **Admixture stabilization using lime and lime-fly ash**—The construction steps associated with using lime to stabilize a poor quality subgrade soil in place are similar to those described above where cement is used as the stabilizing agent. They include spreading the lime, adding water and mixing, compacting, and curing (National Lime Association, 2004). It should be first noted that there are three different types of lime application: dry hydrated lime, dry quicklime, and slurry lime. The type of lime application method used will depend upon contractor experience, equipment availability, location of project (rural or urban), and availability of an adequate nearby water source. For wet soils, dry quicklime is typically the preferred choice. It is usually delivered to the job site in self-unloading transport trucks, but can also be delivered in tarp-covered dump trucks. The basic construction steps associated with the use of quicklime in an in-place soil stabilization process are summarized below:
   - Spreading quicklime—Quicklime is usually spread in one of two ways. The first involves the use of a truck equipped with either an aggregate type spreader or a pneumatic spread bar. Both are designed to spread the lime the full width of the truck. The second common method of distribution is through the use a bottom-dump tanker or clam shell bottom-dump trailer that can drop the quicklime in a windrow. If selected, this method requires a grader.
   - Preliminary mixing and watering—Preliminary mixing is performed to distribute the lime throughout the soil. It is also done to initially pulverize the soil and prepare it for the addition of water. Historically, mixing was achieved through a scarification process using a grader equipped with a ripper. However, modern rotary mixers that add water and mix it with the soil and quicklime are more effective.
   - Mellowing period—For higher plasticity, cohesive soils, a period of 1 to 7 days is required to allow the chemical reaction to break down the soil. Engineering judgment should be used to determine when the “mellowing” process is complete.

- Final mixing and pulverization—Once the mellowing period is complete, the material should be mixed and pulverized until 100 percent of the non-stone material passes the 1-inch sieve and at least 60 percent of the non-stone material passes the No. 4 sieve. The goal is to bring the soil to 3 percent above optimum moisture content (of the treated material). This may require additional moisture during mixing.
- Compaction—Ideally, compaction should begin immediately after mixing; however, delays of up to 4 days are acceptable if the lime-soil mixture is lightly rolled and kept moist. For thicker lifts, compaction can be accomplished in a single lift using heavy pneumatic or vibratory pad-foot rollers. A combination of sheepsfoot and light pneumatic vibratory pad-foot rollers or tamping foot rollers may be used for thinner lifts. Final surface compaction is typically accomplished using a steel wheel roller.
- Final curing—During the curing (hardening) process, the lime-treated soil should be kept moist by either moist curing (light applications of water and rolling) or membrane curing (sealing the surface with an asphalt emulsion prime coat). The lime-treated soil is cured when a loaded dump truck can operate on it without rutting the surface.

The main construction considerations for this method of stabilization are listed below:

- **Climatic conditions**—For the lime-treated soil to cure properly, air temperatures during construction should be greater than 4 °C (40 °F) in the shade. If the purpose of the lime treatment is mainly to dry up a wet soil, the operation can be performed in cooler weather. However, it should never be carried out during freezing weather.
- **Wet weather**—Lime spreading, mixing, and compaction can take place during light rains.
- **Safety precautions**—Lime, especially quicklime, is an alkaline material that reacts to the presence of moisture. It poses hazards to skin, eyes, and lungs. Accordingly, workers must wear proper protective equipment.
- **Other admixtures**—Fly ash can be used along with lime to further improve the properties of the subgrade soil. However, the processes for spreading and mixing are different.

6.2.1.3. Dewatering Systems

The previous two sections describe removal and replacement procedures and stabilization techniques for dealing with a poor subgrade soil that is the result of poor quality materials (such as clays and silts) and saturated or high-moisture conditions. An alternative approach for some new pavement construction projects is the installation of a dewatering system, which is designed to lower the elevation of the wet (saturated) zone of the subgrade soil to a depth where it will have minimal effect on the construction and performance of the pavement. For pavement construction, a dewatering system usually consists of trenches dug to the desired depth along one or both sides of the pavement alignment. In most cases, perforated pipe is installed and the trench is backfilled with a permeable material. If the installation is intended to be permanent, many of the design criteria used for subsurface edge drains are applied. If the topography permits, the water can be allowed to drain to a lower elevation near the construction site. If not, a pump will be required.

A dewatering system can be temporary or permanent. A temporary system will allow the water level to be lowered long enough such that soil in the construction zone will dry, develop some strength and stability, and provide a working platform for the new pavement. After pavement construction is complete, the dewatering system can be uninstalled, removed, or abandoned. This will, of course, allow saturated conditions to return to their original level. However, if the pavement was properly designed and constructed, its behavior and performance will not be significantly affected. In contrast, a permanent dewatering system is one that will continually drain the water from the wet zone so that the increase in soil strength and stability is almost permanent.

6.2.2. Base Placement and Compaction Requirements

In this context, the term "base" by itself refers to any of the unbound aggregate layers used to provide structural support in an asphalt concrete pavement structure. The term *base course* defines the layer directly below the asphalt concrete surface. The base course is usually constructed with crushed aggregate or gravel, although some are constructed as an asphalt- or cement-stabilized material. The *subbase course* is the layer between the base course and the subgrade soil. Because the stress levels on the subbase course are less than those on the base course, it is usually constructed with crushed aggregate, gravel, or engineered fill material that is of slightly lower quality than the base material. Both the base and subbase layers are constructed at specified thicknesses to provide adequate cover over the subgrade soil (to protect from overstress) and to help provide the needed capacity to carry the expected future traffic. These unbound layers are generally not frost susceptible; however, they will suffer some loss of strength when they are exposed to moisture. The loss of strength is dependent on the quality of the material and the amount of time that the materials are saturated.

Typical specifications for both base and subbase courses focus on thickness, density, gradation, fractured faces, liquid limit, plasticity index, strength, and resistance to wear. Usually a dense-graded gradation is used for these courses, although the base course may be open-graded if it is intended to provide subsurface drainage.

The process of constructing base and subbase courses is relatively simple. The materials are hauled to the pavement site using end dump, bottom dump, or side dump trucks, placed directly on grade, spread to a uniform design thickness using graders or dozers, and then compacted to a specified density using vibratory steel wheel rollers (Christopher, Schwartz, and Boudreau 2006). Layer thickness, density, and aggregate gradation should be monitored during construction to ensure conformance to specification requirements.

6.2.3. Asphalt Concrete Placement and Compaction Requirements

The asphalt concrete surface layer in a flexible pavement serves four primary roles:

- **Structure**—The layer should be thick enough and strong enough to carry the anticipated future truck traffic.

- **Ride quality**—The layer should be smooth enough to provide satisfactory ride quality for several years.
- **Surface friction**—The surface should exhibit good frictional characteristics to prevent wet-weather crashes.
- **Moisture barrier**—Unless the asphalt concrete surface layer is intended to be permeable (such as an open-graded friction course), it should be almost impervious to the infiltration of water and have sufficient cross slope to allow water to flow laterally off the pavement.

From a new construction standpoint, there are a number of references that document the best practices needed to help ensure that each of these roles are fulfilled (Asphalt Institute 2001; USACE 2000; Roberts et al. 1996). Following is a summary of the basic steps associated with asphalt paving best practice:

- **Surface preparation**—For new pavement construction or reconstruction, this primarily involves achieving a firm, uniform foundation by properly preparing the subgrade soil and placing, compacting, and shaping/grading the base and subbase layers. For overlay construction, this requires repairing (patching) distressed areas, sealing cracks that might reflect through the overlay, addressing any potential reflection crack issues, and applying a satisfactory tack coat (Figure 6.5) to ensure a strong bond between the new overlay and the existing pavement.

Figure 6.5. Satisfactory Application of Tack Coat on Milled Surface

- **Delivery**—The goal of the asphalt concrete delivery process (which includes truck loading at the hot-mix plant, hauling, and unloading at the paving site) is for the mix to be in the same condition in the hopper of the paver as it was in the silo of the hot-mix plant. This means following the recommended best practices to avoid aggregate segregation and thermal segregation. Aggregate segregation refers to the non-uniform distribution of fine and coarse aggregate in the mix (Figure 6.6). It can occur during the delivery process through improper loading and unloading procedures that allow coarse aggregate in the mix to roll downhill. Thermal segregation refers to the non-uniform distribution of temperature in the mix (Figure 6.7, illustrating temperature differences). It can occur when the mix is allowed to cool non-uniformly during hauling or after unloading in a windrow operation. Again, both forms of segregation can be minimized by employing best practices for loading, hauling, and unloading. However, for situations where segregation-prone mixes are being used, a material transfer vehicle (MTV) with remixing capabilities can be used. Figure 6.8 shows one type of MTV being used to remix the asphalt concrete and also to convey the mix from the haul trucks to the paver hopper in continuous fashion.

Figure 6.6. Aggregate segregation in the hopper of the paver (NHI 2002)

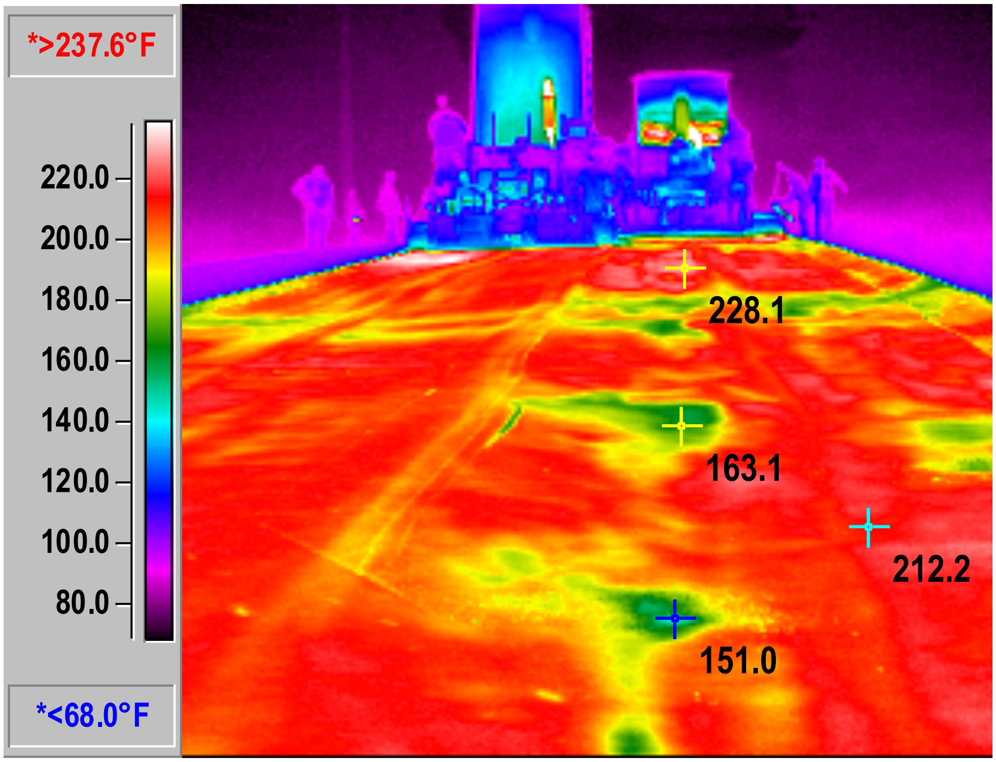

Figure 6.7. Thermal imaging of new asphalt mat indicating hot (red/orange) and cooler (yellow/green) regions (NHI 2002)

Figure 6.8. Material transfer vehicle used to restore mix uniformity and convey mix from haul truck to paver (courtesy of Wisconsin DOT)

- **Paving**—The potential for creating aggregate segregation can also occur as part of the paving process. However, this can be avoided, or at least minimized, by following best practices, such as not folding cool or segregated material in the paver wings into the hopper and making sure that the augers on the back of the paver are uniformly distributing the mix across the width of the mat.
- **Compaction**—Proper rolling of the mat (after it is placed) is essential to achieving the target density of the asphalt mix. For any given situation, there are a multitude of factors that should be considered to determine the combination that works best. Among these are roller type or types (e.g., static steel wheel, vibratory steel wheel, and pneumatic tire), roller patterns, compaction window, and tools available to monitor densification (e.g., nuclear and non-nuclear density gages and intelligent compaction).

The Hot-Mix Asphalt Paving Manual (USACE 2000) provides a useful tool (see matrix in Table 6.2) to help identify and address some of the problems that may be encountered during the construction of an asphalt concrete surface course.

Table 6.2. Mat Problems and Their Causes (USACE 2000)

Problem	Fluctuating Head of Material	Feeder Screws Overloaded	Finisher Speed Too Fast	Too Much Lead Crown in Screed	Too Little Lead Crown in Screed	Overcorrection of Thickness Control Screws	Excessive Play in Screed Mechanical Connection	Screed Riding on Lift Cylinders	Screed Plates Worn Out or Warped	Screed Plates Not Tight	Cold Screed	Moldboard on Strickeoff Too Low	Running Hopper Empty Between Loads	Feeder Gates Set Incorrectly	Kicker Screws Worn Out or Mounted Incorrectly	Incorrect Nulling of Screed	Screed Starting Blocks Too Short	Screed Extensions Installed Incorrectly	Vibrators Running Too Slow	Grade Control Mounted Incorrectly	Grade Control Hunting (Sensitivity Too High)	Grade Control Wand Bouncing on Reference	Grade Reference Inadequate	Sitting Long Period Between Loads	Improper Joint Overlap	Improper Mat Thickness for Max. Agg. Size	Trucks Bumping Finisher	Truck Holding Brakes	Improper Base Preparation	Improper Rolling Operation	Reversing or Too Rapidly Turning Rollers	Parking of Roller on Hot Mat	Improper Mix Design (Aggregate)	Improper Mix Design (Asphalt)	Mix Segregation	Moisture in Mix	Variation of Mix Temperature	Cold Mix Temperature
Wavy Surface – Short Waves (Ripples)	√	√	√				√	√		√										√	√	√	√						×	×			×	×	×		×	
Wavy Surface – Long Waves	√	√				√	√	√					√	√						√			√	√			×	×	×		×	×			×		×	
Tearing of Mat – Full Width			√						√		√															×							×	×	×	×	×	×
Tearing of Mat – Center Streak					√				√		√			√	√																							×
Tearing of Mat – Outside Streaks				√					√		√	√		√				√																				×
Mat Texture – Nonuniform	√	√	√					√	√	√	√		√					√	√					√		×			×				×	×	×		×	×
Screed Marks							√																				×	×										
Screed Not Responding to Correction			√				√	√		√										√						×											×	×
Auger Shadows		√																															×	×	×			
Poor Precompaction			√					√											√							×			×									×
Poor Longitudinal Joint	√	√				√		√												√	√	√			√					×								×
Poor Transverse Joint		√					√	√		√						√	√													×								×
Transverse Cracking (Checking)																													×	×			×	×		×	×	
Mat Shoving Under Roller																													×	×	×		×	×		×	×	
Bleeding or Fat Spots in Mat																																	×	×		×	×	
Roller Marks																													×	×	×	×					×	
Poor Mix Compaction																													×	×	×	×	×	×		×	×	×

1. Find problem above
2. Checks indicate causes related to the paver
   X's indicate other problems to be investigated

NOTE: Often a problem has more than one cause. Therefore, it is important that each cause listed is eliminated to ensure that the problem will be solved.

For the purposes of these guidelines, the focus is on the best construction practices needed for the asphalt concrete layer to serve as a moisture barrier. As discussed in Chapter 3, one of the entry points for moisture into a pavement is through the surface layer. Existing cracks, open construction joints, and, in the case of an asphalt concrete surface layer, high air voids, will allow moisture to infiltrate the pavement. There are two keys to reducing the development of cracks:

keeping construction joints from opening and deteriorating, and preventing interconnected air voids in the asphalt concrete layer. The first is accomplished by ensuring that the asphalt mix meets the requirements for asphalt binder content and the second by making sure that the mat meets density requirements. Standard dense-graded asphalt mixes are typically designed to have enough asphalt binder so that, with proper compaction, the air voids in the mix will be about 4 percent by volume of mix. The binder content corresponding to that level of air voids will help ensure that all of the aggregate particles are adequately coated and that there are no interconnected air voids that would allow moisture to infiltrate the surface.

6.2.3.1. Ensure Proper Binder Content

The asphalt binder content is controlled at the hot-mix plant. Consequently, it is the responsibility of the plant operator to take the necessary steps that will ensure that the required quantity of asphalt is going into the mix. An important aspect of this process (which is also part of a sound quality control program) is routinely taking samples of the mix during production, determining the actual binder content, and then making corrections as necessary. Monitoring the binder content (as well as other key mix characteristics) during production will not only help correct small deviations, but it will also help identify any equipment problems at the plant.

The responsibility of the owner/agency in the construction process is to employ a statistically valid, random sampling and testing program (as part of an overall quality assurance program) to confirm that the binder content of the mix is within the range set forth in the specifications. Note, however, that this random sampling and testing process is applicable to other key characteristics of the mix too.

6.2.3.2. Proper Compaction of the Asphalt Concrete Mat

There are several key elements to compacting the asphalt concrete mat that are necessary to achieve the target density uniformly throughout the mat:

1. **Roller selection**—The self-propelled rollers that are used for compacting the mat fall into three categories (static steel wheel, pneumatic tire, and vibratory steel wheel). For a given project, a roller or combination of rollers should be selected to not only achieve the target density in a cost-effective fashion, but also address the unique characteristics of the mix (e.g., some mixes do not compact well at certain temperatures) and the project site. Static steel wheel rollers are typically used for initial (breakdown) rolling and finish rolling. Considerations in their selection include roller weight, drum dimensions, and contact pressure. Pneumatic (or rubber) tired rollers are mostly used for intermediate rolling, although they have been used to assist in breakdown and finish rolling. Compared to steel wheel rollers, they combine kneading and compacting, which is an advantage for some mixes. Other considerations in using pneumatic tired rollers include tire pressure and potential for mix pick-up. Vibratory steel wheel rollers, which introduce a vibratory element of compaction through an eccentric shaft in the drum, can be used for breakdown, intermediate, and finish rolling, although they are primarily used for breakdown rolling. The vibratory component, along with the rollers' dead weight, make vibratory rollers very efficient at compacting the mix. The key factors considered for a

vibratory roller on a given project include roller weight and the frequency, amplitude, and impact spacing of the vibratory system.

2. **Roller operation**—For large paving projects, test strips should be constructed to confirm the roller selection and establish a roller pattern that should be used for the remainder of the project (unless the mix design changes). Standard roller patterns are used as a starting point; however, to be complete they need to establish roller speed and other roller characteristics such as tire pressure for pneumatic tire rollers and frequency and amplitude for vibratory rollers. Roller patterns will vary depending on the type of mix and the type of project, but once established it is important to require that roller operators actually follow the roller pattern.
3. **Available time for compaction**—Once the mix is laid on the pavement, there is a limited time available to achieve the target density before the mix cools. This "compaction window" is dependent upon a number of factors such as air temperature, solar radiation, mix temperature, and wind speed. Software tools (and smart phone apps) are available to determine the compaction window (see, for example, http://www.dot.state.mn.us/app/pavecool/index.html.
4. **Testing for in-place density**—The traditional and most common tool used to determine if the target density is achieved is the nuclear density gauge. In simple terms, it uses a small radiation source to emit particles into the mat and then detects the number of those particles that are reflected. By correlating that count with the actual density test results on samples from the same mix, the device can be used in the field to estimate in situ density. Because of the radiation issues associated with nuclear gauges, a new type of test equipment, referred to as non-nuclear gauges, was developed. These devices obtain an estimate of the dielectric constant of the mat and, in a manner similar to the nuclear gauge, correlate the dielectric constant to lab density results obtained from core samples. For both the nuclear and non-nuclear gauge, calibration is essential to achieving a valid estimate of the in-place density of the mat.

   Although it does not replace lab testing of cores or even the nuclear and non-nuclear methods of testing for in place density, a new technology has emerged that allows contractors to better monitor the densification of the mat during rolling. The new technology, referred to as intelligent compaction (IC), uses a combination of accelerometers mounted on the axle of the roller, a GPS antenna to track the roller location, and infrared cameras to monitor the temperature of the mat. This technology provides the roller operator with visual (color-coded) feedback on how well densification is being achieved. Figure 6.9 shows the use of vibratory steel-wheel rollers equipped with intelligent compaction instrumentation that allow roller operators to monitor the densification of the mat.

Figure 6.9. Asphalt Pavement Construction Project Using Rollers Equipped with Intelligent Compaction Instrumentation to Monitor Densification (Courtesy of Lee Gallivan)

6.2.3.3. Proper Compaction of the Longitudinal Joint

The longitudinal joint between paving lanes is one of the most likely locations where moisture will infiltrate the pavement. When poor paving and poor joint compaction practices are employed, the joint can separate and behave like an open longitudinal crack (Figure 6.10). In wet weather, it will intercept moisture flowing toward the pavement edge and increase the potential for moisture damage along the joint and the likelihood of weakening the subsurface layers.

Figure 6.10. Moderate Severity Longitudinal Joint Separation and Raveling Between Paving Lanes

Limiting the potential for this type of distress to occur and its ramifications involves ensuring that 1) adequate material is available at the joint prior to rolling, and 2) the joint is rolled in a manner that allows for satisfactory density. The best practice steps required to achieve satisfactory longitudinal joint density include:

- Rolling the unsupported edge with a 152 mm (6-in.) overhang of a steel wheel roller.
- Paving against the cold joint in an adjacent lane leaving a 25- to 38-mm (1- to 1.5-in.) strip of mix on the edge of the cold side.
- Using the lute to "bump back" the strip of mix so that it can be easily rolled into the joint. (In no case should the material be cast back into the mat).
- Rolling the longitudinal edge along the cold joint with a 152 mm (6-in.) overhang of the roller so that the mix can be densely compacted into the joint. Another option is for the roller to hold off the joint by 152 to 305 mm (6 to 12 in.) during the first pass and then compact the 152 to 305 mm (6 to 12 in.) strip during the second pass.

6.2.4. Concrete Pavement Design and Construction Considerations in New Composite Pavement Systems

New composite pavement systems feature a new asphalt pavement surface placed on top of a new concrete pavement. Although composite pavements are traditionally thought of as overlays of existing concrete pavements, a number of agencies are constructing new composite pavements systems in order to obtain several key benefits, including extended service life, a renewable surface, and increased sustainability (Rao et al. 2013). In the design and construction of new composite pavement systems, there are several opportunities to minimize the potential adverse impacts that moisture could have on their performance and longevity.

6.2.4.1. Base Courses for Composite Pavements

As described previously, the use of nonerodible or moisture-insensitive base materials beneath a pavement can help reduce or delay the development of pumping, faulting, and other moisture-related damage; this is particularly important for pavements exposed to higher traffic volumes and located in a wet climate (Smith and Hall 2001). Types of nonerodible or moisture-insensitive bases are listed below (Smith and Hall 2001; ACPA 2007a):

- **Lean concrete base (LCB)**—A lean concrete base is similar to conventional paving concrete in makeup and composition, but generally contains less cement and therefore has lower strength than conventional paving concrete. It provides uniform support to the concrete and a strong construction platform, but is more expensive than other base types. In addition, the relative stiffness of the base can contribute to random cracking in the concrete pavement if shorter joint spacings are not employed. A granular subbase separating the lean concrete base from the subgrade soil is recommended.
- **Cement-treated base (CTB)**—A cement-treated base is a dense-graded aggregate mixed with about 6 to 8 percent portland cement for roadways carrying medium to high volumes of heavy traffic. Cement-treated bases are easy to construct and provide a stronger and more erosion-resistant platform for the concrete slab than a granular base; however, they

are slightly more expensive and can still be susceptible to erosion depending on the amount of cement and degree of consolidation. A granular subbase separating the cement-treated base from the subgrade soil is usually needed to prevent pumping.

- **Asphalt-treated base (ATB)**—An asphalt-treated base is a dense-graded aggregate mixed with about 5 to 6 percent bituminous binder, usually either an asphalt emulsion or an asphalt cement. Asphalt-treated bases are easy to construct and provide a stronger and more erosion-resistant platform for the concrete slab than a granular base. The effectiveness of an asphalt-treated base will be diminished if stripping occurs, so minimizing the susceptibility to stripping (using compatible aggregates and binder) should be considered in the mix design. A granular subbase separating the asphalt-treated base from the subgrade soil is usually needed to prevent pumping.

6.2.4.2. Concrete Pavement Jointing Details

Transverse and longitudinal joints (Figure 6.11) are placed in concrete pavements primarily to prevent the development of uncontrolled, random cracking, but are also used to facilitate overall construction activities and to isolate the pavement from abutting structures (Smith and Hall 2001). A detailed jointing plan—including details for the layout and design of both transverse and longitudinal joints—reduces the risk of random cracking and helps to ensure the long-term performance of the concrete pavement, and is particularly important in complicated jointing situations such as intersections (ACPA 2007b). Uncontrolled, random cracks can create reflection cracks in the asphalt surface layer, which can then serve as entry points for moisture to infiltrate the pavement structure and weaken the foundation support layers.

Figure 6.11. Transverse and Longitudinal Joints on Concrete Pavement

Jointing details and layouts are often based on experience or agency standards, but transverse joint spacing is a direct input into the Pavement ME design procedure. That design procedure considers the interactive effects of slab thickness, joint spacings, foundation support, traffic loadings, and climatic conditions to predict performance, enabling design engineers to determine the effects of varying transverse joint spacings and then to optimize overall designs. For most highway pavements (typical thicknesses of 254 to 305 mm [10 to 12 in.]), a maximum transverse joint spacing of 4.6 m (15 ft) is recommended, and these joints should line up across adjacent traffic lanes or shoulders (AASHTO 2015). Pavements with thinner slabs or placed on a stabilized base course may require shorter joints spacings (Smith and Hall 2001). It is further recommended that transverse joints be placed perpendicular to the pavement centerline and at uniform (nonvariable) spacing (AASHTO 2015).

Longitudinal joints are placed to eliminate uncontrolled longitudinal cracking. Typically, these longitudinal joints are placed to create slab widths of 3.7 m (12 ft), which conveniently matches most traffic lane widths. Longitudinal joints spaced more than about 4.3 to 4.6 m (14 to 15 ft) apart will result in the development of longitudinal cracking, which could reflect through the asphalt surface and create an entry point for moisture. In the layout of longitudinal and transverse joints, some agencies target slabs that are square (or nearly so) by requiring that the ratio of the slab length (in the direction of traffic) to the slab width (perpendicular to traffic) be less than 1.5, with some agencies limiting it to no more than 1.25. For example, a 3.7-m (12-ft) wide concrete pavement with transverse joints spaced at 4.6 m (15 ft) produces a length-to-width ratio of 1.25.

Sawing is the most common means of creating weakened-plane contraction joints in concrete pavements (Figure 6.12). The sawing of these weakened-plane transverse and longitudinal contraction joints should begin as soon as possible after the concrete is strong enough to support the sawing equipment; this is often between 4 and 12 hours after placement, but can vary considerably depending on the properties of the concrete and the prevailing climatic conditions (ACPA 1991). The goal in timing the sawcutting operation is to not saw too soon (which will cause raveling of the concrete) nor too late (which may result in random cracking). At the same time, it is important that the joints be sawed deep enough in order for the weakened plane to develop; typically a depth of 1/3 of the concrete slab thickness is specified for both transverse and longitudinal joints (Smith and Hall 2001).

Figure 6.12. Weakened Plane Sawcut That Has Produced a Crack Beneath the Cut

6.2.4.3. Joint Load Transfer

As shown conceptually in Figure 6.13, load transfer refers to the ability of a joint to transfer traffic loading from one slab to another. Load transfer is most effectively provided by mechanical devices (most commonly, round, smooth steel dowel bars) placed across joints at the mid-depth of the slab. This method is not only highly effective at transferring load from one side of the joint to the next (which reduces pumping and faulting), but also reduces tensile stresses in the slab corners (which prevents corner breaks).

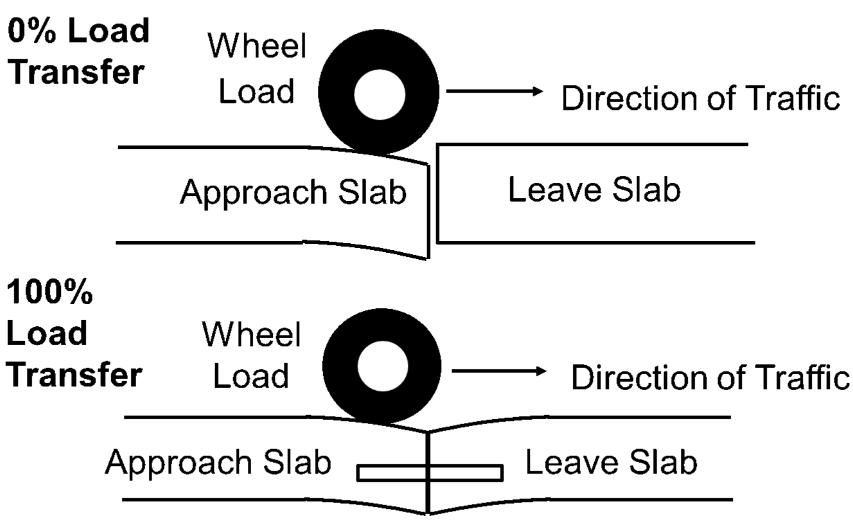

Figure 6.13. Concept of Joint Load Transfer Efficiency

The use of dowel bars is recommended for most highway pavements, even if used as part of a composite pavement structure. This will help minimize the effects that excess moisture or poor drainage conditions may have on the underlying support layers. Most agencies are moving to larger diameter dowel bars to provide enhanced load transfer capabilities, and for most highway pavements (on the order of 254 to 305 mm [10 to 12 in. thick]), a 38-mm (1.5-in.) diameter dowel bar is recommended (Smith and Hall 2001). Dowel bars are positioned so that they are located at mid-depth of the slab at 305-mm (12-in.) intervals across the slab (although some agencies are moving to clustering three to five dowel bars in each wheelpath).

Moisture in the joint can also contribute to corrosion of the dowel bars. Dowels should be coated with a corrosion inhibitor (e.g., epoxy) to help ensure the long-term effectiveness of the bar. Dowels made with alternative, noncorrodible materials (e.g., stainless steel, glass fiber reinforced polymer) are seeing some use to eliminate the potential for corrosion and the associated reductions in pavement performance (Smith 2002).

Tiebars are used in concrete-to-concrete longitudinal joints, such as between adjacent concrete traffic lanes or between a concrete lane and concrete shoulder. The tiebars are not for load transfer, but instead are intended to help keep the longitudinal joint held tightly together and in vertical alignment. Like dowel bars, these tiebars are located at mid-depth of the slab and should be epoxy coated for moisture resistance and long life. For most highway facilities, No. 5 or No. 6 deformed, epoxy-coated tiebars (762 mm [30 in.] long and spaced at 762-mm [30-in.] intervals) are recommended (Smith and Hall 2001). Figure 6.14 shows the layout of both dowel bars (for transverse joints) and tiebars (for the lane-lane longitudinal joint) on grade prior to the placement of the concrete.

Figure 6.14. Dowel Bars and Tiebars on Grade Prior to Paving

6.2.4.4. Placement of Asphalt Cold Joints

As an additional step to minimize moisture infiltration into the underlying concrete pavement, the asphalt paving widths should be offset from the longitudinal joints in the concrete pavement. This will eliminate an asphalt cold paving joint at that location, which could be susceptible to cracking and deterioration and thereby serve as a ready entry point for water.

6.2.5. Construction Quality Control and Acceptance

For the purposes of this guide, the standard definitions in AASHTO's R 10-06 (2011) *Standard Practice for Definition of Terms Related to Quality and Statistics as Used in Highway Construction* are used to discuss the quality control and acceptance issues associated with pavement construction. Accordingly, as part of an overall quality assurance (QA) program, quality control (QC) is the responsibility of the contractor and acceptance is the responsibility of the owner/agency. To have an effective QC operation, the contractor must monitor and adjust his production and construction processes to ensure that the final product meets the specified level of quality. Acceptance refers to the process whereby all factors used by the agency (i.e., sampling, testing, and inspection) are evaluated to determine the degree of compliance with contract requirements and to determine the corresponding value of the as-constructed pavement (for payment purposes).

6.2.5.1. Testing Requirements

Regardless of the pavement layer, material testing is required for both QC and acceptance. The test methods vary depending on the layer characteristics, although they tend to be the same test method for both processes. The difference is that QC testing is generally performed at frequent, uniform intervals to control the production and stay within specified limits, while acceptance testing is performed on a randomized, statistically-valid, lot-by-lot basis to establish acceptance and final payment.

From the standpoint of minimizing the potential for moisture damage, the materials and properties that should be strictly controlled and enforced during pavement construction are shown in Table 6.3.

Table 6.3. Key Material Properties and Characteristics That Should be Strictly Controlled to Help Ensure Good Resistance to Moisture Damage

Pavement Layer	Key Material Tests Needed to Ensure Good Resistance to Moisture Damage					
	Thickness	**Density**	**Asphalt or Cement Content**	**Additive/ Admixture Content**	**Gradation**	**Strength**
Asphalt Concrete	√	√	√		√	
Base/ Subbase	√	√			√	
Asphalt-Stabilized Base	√		√			
Lime or Cement Stabilized Base	√			√		√
Gravel/Lightweight Fill		√				
Subgrade Soil		√				

6.2.5.2. Monitoring Procedures

For most pavement construction projects, the owner/agency will deploy construction inspectors to the job site on a daily basis for many of the following reasons:

- Monitor construction.
- Enforce material requirements and construction practices set forth in the specifications.
- Work with the contractor to resolve problems as they arise.
- Keep a log of activities, inspection results, and contractor agreements.
- Generally look after the best interests of the agency/owner.

The inspectors may be employees of the owner/agency or a consultant hired to serve in the inspector role on behalf of the owner/agency, but their efforts are part of the owner/agency's acceptance role.

As each layer of a new pavement is constructed, there are a number of key inspection items that should be carefully observed to help correct any potential issues that may lead to moisture damage issues. Table 6.4 provides a list of those key inspection items by pavement layer.

Table 6.4. Key Construction Inspection Items that can Help Avoid Moisture Damage Problems in a New Pavement

Pavement Layer	Key Construction Inspection Items
Asphalt Concrete	• Check the truck weight ticket to make sure that the specified mix is being delivered. • Check the mix in the haul truck to make sure that the aggregate segregation is minimal and the mix temperature is well above the minimum specified. Also, inspect the mix visually to determine if the binder content appears adequate. • During paving, make sure that an adequate thickness is being applied and the proper roller patterns are being followed. • During compaction, watch for signs of mix tenderness and, if necessary, revise the rolling pattern. • While rolling against a cold longitudinal joint, make sure that there is adequate mix along the longitudinal joint so that, when compacted, there will be adequate density along the joint.
Base/Subbase	• Check the weight ticket to confirm that the right material is being used. • Make sure that enough material is dumped to meet the thickness requirements. • Observe compaction to make sure that adequate effort is applied to achieve target density.
Asphalt-Stabilized Base	• Check the weight ticket to confirm that the right material is being used. • Check mix for excess segregation and minimum temperature. • Monitor paving to confirm thickness and density.
Lime or Cement Stabilized Base	• Check the weight ticket to confirm that the right material is being used. • Monitor application of lime or cement to confirm the proper amount. • Observe mixing to ensure material uniformity. • Ensure proper cure type and time. • Confirm microcracking operation (as necessary) after curing.
Gravel or Lightweight Fill	• Check truck weight ticket to confirm the material. • Make sure that enough material is dumped to meet the thickness requirements. • Proof roll as necessary to identify any soft or weak spots.
Subgrade Soil	• After initial grading, proof roll to identify any soft or pumping locations that may need correction. • Monitor compaction to ensure adequate effort is applied to achieve target density. • Observe compaction to make sure that adequate effort is applied to achieve target density.

6.3. Drainage System

A synthesis of pavement subsurface drainage system practices (Christopher and McGuffey 1997) documented a clear connection between premature pavement failures and inadequate subsurface drainage. Although poor drainage design can play a role in some of these early failures, poor construction practices and damage to the drainage system during construction played a significant role in causing the premature failures as well; therefore, it is extremely important to properly construct and install pavement and drainage systems (Christopher and McGuffey 1997). This section will discuss the installation, inspection, and quality control of drainage systems for new pavement construction. The two drainage systems discussed in this section are drainable bases and edgedrain systems.

Drainable bases (stabilized or unstabilized) are base layers placed beneath the HMA pavement surface layer to facilitate the rapid removal of excess moisture from beneath the pavement structure. This quick drainage of moisture is achieved because the permeability of the base allows moisture entering the system to drain quickly away from part of the pavement that is subject to traffic loading.

Edgedrain systems refer to a network of longitudinal drains and drainage outlets that collect water from the pavement system and transport it to a ditch along the side of the roadway. When designed and installed correctly, drainable bases and edgedrain systems work effectively to quickly remove moisture from the pavement system.

6.3.1. Excavation, Placement, and Compaction

Prior to the commencement of new construction, sufficient preparation of the subgrade must be complete before starting to install the drainage system. This is accomplished by making sure that all necessary material and equipment are available and are adhering to the design requirements and construction schedule as best as possible. A Minnesota Department of Transportation (MnDOT) drainage manual offers the following construction sequence for drainage system installation (Arika, Canelon, and Nieber 2009):

1. Prepare the subgrade.
2. Excavate the collector and outlet pipe trenches.
3. Place bedding material.
4. Install perforated pipe in collector trenches.
5. Install outlet pipes.
6. Place and compact trench backfill.
7. Place and compact the separation layer or geotextile layer.
8. Place and compact the drainable base layer.
9. Install outlet appurtenances and markers.

New pavement construction, including the construction and placement of associated drainage systems, can be performed efficiently and precisely using modern construction techniques and equipment (Christopher, Schwartz, and Boudreau 2006).

Some form of excavation is usually required on new construction sites to remove poor quality soil and replace it with a higher quality material. Excavation operations should follow the recommendations provided earlier in Section 6.2.1, which discusses the different considerations that need to be made and the different types of equipment that should be considered for use during excavation operations. Long-term pavement performance issues are at times related to insufficient excavation to completely remove poor and undesirable material; therefore, it is important for designers to perform a thorough subsurface investigation before finalizing the pavement design and for construction teams to fully execute the excavation plan provided by the design engineers.

After excavation is complete, the subgrade soil must be sufficiently prepared before any separation layers or drainable base layers are placed. Characteristics of a prepared subgrade soil include meeting the required grades and capability to support construction traffic

The installation of an aggregate separation layer or a geotextile on top of the subgrade is recommended prior to the placement of the drainable base or other draining systems. If an aggregate layer is used as a separation layer, it is important to follow recommended aggregate gradations for the underlying subgrade material to ensure that fines from the subgrade do not migrate and contaminate the drainable base layer. Figure 6.15 shows the location of an aggregate separator layer in a pavement structure (Arika, Canelon, and Nieber 2009).

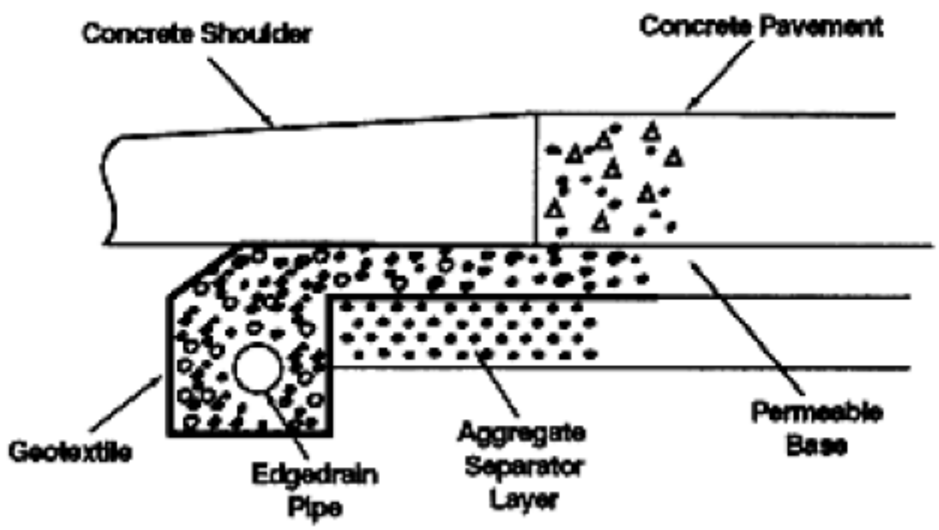

Figure 6.15. Location of separator layer (Arika, Canelon, and Nieber 2009)

If geotextiles are used as separator layers, the geotextile type and specification should meet the design requirements so that it can effectively separate the subgrade soil from the drainable base. Factors to consider while selecting a geotextile as a separator layer include the shape and size of the aggregate that will be placed on top of the geotextile. The goal is to prevent the intrusion of fine materials from below (Christopher, Schwartz, and Boudreau 2006).

During the placement of the drainable base, it is important to ensure that segregation does not occur, especially if an unbound material is used. Accordingly, consideration should be given to the use of equipment and practices that can help mitigate the risk of aggregate segregation during the placement of an unbound drainable base. For spreading unbound base materials, tracked graders and pavers are recommended over those with rubber tires to reduce the risk of rutting in the base.

In the case of a drainable layer constructed with either an asphalt- or cement-stabilized base material, placement and compaction should be done at appropriate temperatures and sufficient time should be allowed for the material to fully cure. It is highly recommended that drainable base layers not be subjected to traffic or used to support construction traffic to avoid damaging the layer or contaminating it with fines. Construction material delivery vehicles may use a side delivery operation to avoid using the drainable base. Compaction of drainable bases should be limited since the purpose is to seat the aggregates rather than reach maximum density. Over-compaction will damage the material and cause densification that may render the layer less permeable (FHWA 2002).

Two edgedrain installation processes are widely used during construction of new pavements. Edgedrains are either installed prior to the construction of the mainline pavement or are installed after the mainline paving has been completed. The latter is achieved by digging trenches towards the edge of the pavement and installing edgedrains. There have been reports where installation of edgedrains during the construction of the pavement has led to the damage or contamination of the edgedrains. There have also been reports that installing edgedrains by digging trenches has resulted in the placement of the edgedrains at the wrong elevation/grade where they are not in contact with the drainable base, rendering them non-functional. Both methods of installation have benefits and drawbacks; therefore, it is important that the designers and construction team communicate to determine which method best suits the specific project (Christopher and McGuffey 1997).

If edgedrains are placed prior to the completion of all the pavement layers, adequate care must be taken when placing the edgedrains so that they are not damaged or contaminated during installation. If contamination or damage of the edgedrain is expected due to additional construction activities, temporary edgedrains should be used so that the pavement will still be able to drain during construction. Edgedrains should be placed at the appropriate elevation (connected with the drainable base or no more than 51 mm [2 in.] below the drainable base) and should be placed at the right grade to ensure the free and uninterrupted flow of water). Perforated edgedrains should be covered in geotextile on all sides except where in contact with the drainable base to avoid the intrusion of fine-grained materials that could lead to clogging. The edgedrains should be connected to outlets at the proper grade so that the moisture can freely exit the pavement structure. The backfill material used for the edgedrain should be as permeable as the edgedrain material and proper care should be taken to avoid accidentally introducing a moisture barrier during construction. The backfill material should also be placed and compacted properly so that the underlying edgedrain is not damaged (Christopher, Schwartz and Boudreau 2006).

If edgedrains are installed after the mainline pavement is constructed, excavation of a trench and placement of the edgedrain system is necessary. Trenches should be excavated so that the top of the edgedrain is around 51 mm (2 in.) below the base course. The trench excavation should also consider that the edgedrains must maintain constant grade. Typically, enough space is made available below the edgedrain to allow for the placement of bedding material (Arika, Canelon, and Nieber 2009). The purpose for the bedding material below the drain pipe is to help protect it from damage during backfill and compaction. The problem with bedding material is that it allows water to stand in the trench below the drain pipe. To prevent standing water, Virginia DOT has adopted the practice of not using bedding material and placing the drain pipe at the bottom of the trench (VDOT 2016). Figure 6.16 provides a pavement cross section of the retrofit edgedrain configuration used by VDOT.

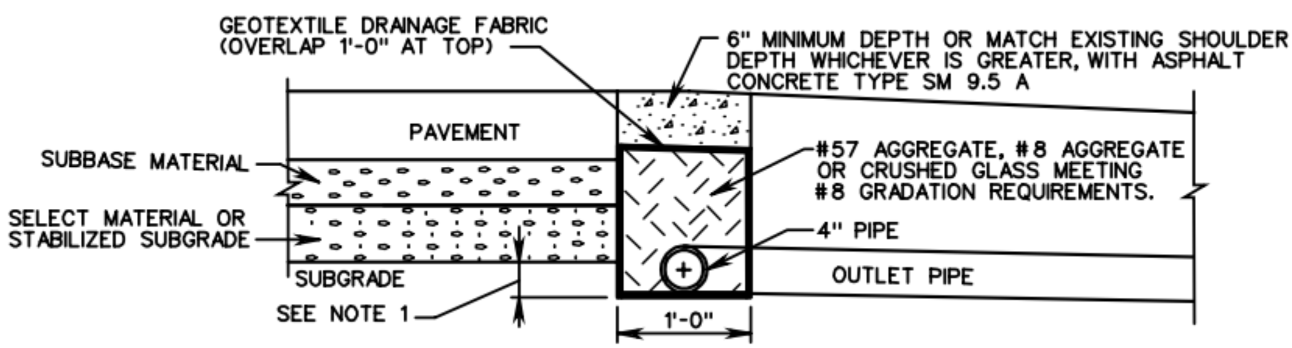

Figure 6.16. Retrofit Edgedrain Configuration With Drain Pipe on Bottom of Trench (VDOT 2016)

Concrete headwalls should be installed at the termini of outlet drains so that they are not damaged by vehicles or mowing operations. The discharge pipe connected to the outlet drain should be well secured to the edgedrain system so that it does not separate from the edgedrain system. Along with the installation of the concrete headwall, a grated metal screen should be installed so that it prevents rodents, animals, and other objects from entering the drainage system. Outlet locations should be clearly and permanently marked to facilitate their location for future maintenance. Figure 6.17 illustrates the typical drainage outlet.

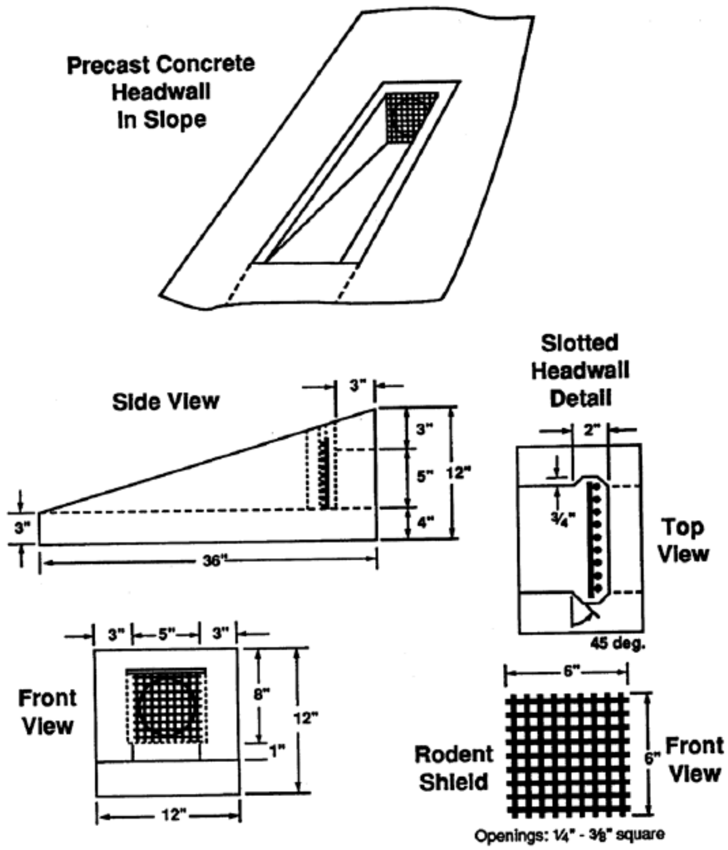

Figure 6.17. Drainage system outlet (Arika, Canelon, and Nieber 2009)

6.3.2. Construction Quality Control and Acceptance

The same basic construction quality control and acceptance practices described in Section 6.2.5 for pavement layers are also applicable for the installation of drainage systems. The contractor is responsible for carrying out the necessary quality control procedures to ensure that the end product meets the specification requirements. The owner/agency, on the other hand, is responsible for employing valid acceptance practices. The following subsections address the typical owner/agency testing requirements and monitoring procedures.

6.3.2.1. Testing Requirements

Inspectors should survey the construction site post-excavation to confirm that the excavation plan was properly executed and that no organic or poor-quality soil remains on the surface before the next stage of the construction. If there is a concern that construction traffic may damage the drainage system, the inspector should consider dynamic cone penetrometer testing (ASTM D6951) to ensure that the drainage systems can support the loading.

Inspectors should be present during the placement of the drainable base layer to make sure that segregation of the aggregate does not occur in unbound drainable bases. For stabilized bases, it is important that the inspector ensure that material has properly cured. Inspectors should also perform density measurements of the compacted drainable base. Density requirements could be established by setting up test strips and determining the maximum density achieved by compaction without damaging the material; for example, 95% of maximum test strip density could be used for acceptance of compacted drainable bases (FHWA 2002). For acceptance of the drainage system to be confirmed, inspectors should examine the drainage system to verify that it is working according to specifications. Inspectors can also test the drainable base and edgedrain system by pouring water into the pavement at a predetermined location and monitoring the flow of water at the edgedrains (Christopher, Schwartz, and Boudreau 2006). If there is a problem with outflow, the edgedrain system could also be inspected by video according to the details provided in Section 6.3.2.2.

6.3.2.2. Monitoring Procedures

Ongoing monitoring of the drainage system is important to make sure that moisture is drained away from the pavement structure efficiently throughout the life of the pavement. Monitoring and maintenance of drainage systems is significantly cheaper than correcting the damage caused to pavements due to faulty and malfunctioning drainage systems. Therefore, it is very important to continue to monitor and maintain drainage systems over the life of the pavement. Monitoring operations could be scheduled together with other routine operations such as pavement condition assessments and the results of these monitoring activities should be documented in an easily accessible database. Drainage function monitoring could be integrated into pavement management systems so that the drainage information is readily available to pavement managers and engineers along with other pavement performance data.

The easiest way to continue monitoring draining systems and make sure there is no blockage is to incorporate the video monitoring system discussed in Section 6.3.2.1. A random portion of the edgedrain system could be monitored using video monitoring on a frequent schedule to make sure that problems are caught and resolved in a timely manner. Structural deficiencies identified in the drainable layer could be caused by factors that adversely affect the drainage capabilities of the layer. Damage caused to the drainable layer could cause the reduction of the air voids which may lead to decreased drainage potential. When performing structural testing such as FWD testing, it is important to maintain a testing program over several years so that the pavement structure and the drainable layer could be monitored for any change in condition. Only when time-series data is available could engineers notice changes in the performance of the drainable layer over the long term. It is also advisable to get a baseline measurement immediately after construction for future use in comparative analysis (Christopher and McGuffey 1997).

The observations and results gathered through continued monitoring should be part of a feedback loop and shared with design and construction groups so that these observations could be incorporated in future design and construction of pavement drainage systems. Only through a continuous feedback loop will drainage systems maintain their functionality over time (Christopher and McGuffey 1997).

6.4. Roadway Widening

Roadway widening involves a lateral extension of the existing roadway beyond the inner or outer limits of the existing pavement alignment. Widening is usually required to improve safety or to increase the capacity of the existing roadway. Widening may involve a) adding 0.61 to 1.22 m (2 to 4 ft) to the width of the pavement lane or shoulder, b) adding an entire lane (or lanes), or c) simply adding a shoulder. From the drainage perspective, widening an existing roadway can pose unique problems in developing the structural and geometric design requirements for the widened pavement. Following is a list of drainage-related factors that should be considered in the design process (Hilbrich and Scullion 2007).

1. Vertical construction face between the existing structure and widened pavement—The problem with the vertical face is that, over time, it is likely to separate and create a path for moisture to infiltrate the pavement. This is especially a problem if the vertical face is in or near a wheelpath.
2. Match structural section—Consider matching the structural section in the widened pavement with the structural section in the existing pavement, especially if the existing pavement includes a moisture-susceptible layer. Also, consider using ground penetrating radar (GPR) to identify any significant changes in existing pavement structure that might affect the structural selection in the widened pavement.
3. Permeability—If the existing pavement includes a permeable base layer, then the permeability of the base used in the widened pavement should be the same or higher. Ensure that the design for the widened pavement provides for moisture to exit the pavement (and not allow it to feed back in).
4. Existing edge drain—If there is an existing edgedrain in the area to be widened, it should be removed and either replaced with an edge drain at the new pavement edge or left out completely. Paving over an existing edge drain (and extending the outlet pipes to the new edge) may seem reasonable. However, it could eventually become clogged and retain water rather than remove it.
5. Widening a jointed concrete pavement—An existing JCP can be widened with an asphalt concrete pavement. However, use of an aggregate base is not recommended. It is also critical to get good density in all layers if the widened pavement structure.

Finally, with the longer length of the drainage path associated with a widened pavement, there may be some geometric issues to address, such as the pavement cross slope.

6.5. Summary

This chapter provides guidance on how to address potential moisture damage problems and drainage issues at a time where they could be more cost effectively considered (i.e., during the planning, design, and pre-construction stages). Subsections cover the a) the subgrade soil and the individual layers that make up the pavement structure, b) the drainage systems that are intended to carry moisture away from the pavement, and c) the key considerations for roadway widening.

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CHAPTER 7. MAINTENANCE AND PRESERVATION STRATEGIES

7.1. Introduction

Timely pavement maintenance and preservation can help to retard the development or progression of moisture-related damage to flexible and composite pavements by repairing or sealing locations where water enters the pavement structure, by slowing the rate of surface deterioration that leads to the development of distresses which allow water to enter the pavement structure, or by sealing or waterproofing the entire pavement surface. A common approach to classifying these strategies is to define the repairs to existing localized distresses as *maintenance* and to categorize the blanket repairs that target the entire pavement surface and are intended to slow the development of distress as *preservation*. This chapter covers those two topics, along with a discussion on the maintenance of drainage features.

7.1.1. Maintenance Strategies to Reduce Moisture Infiltration

Pavement maintenance may be required at any time in the life of a pavement in order to keep the pavement in serviceable condition. The two most common maintenance activities performed on flexible and composite pavements to reduce moisture infiltration are crack sealing and filling and pavement patching.

7.1.1.1. Crack Sealing and Filling

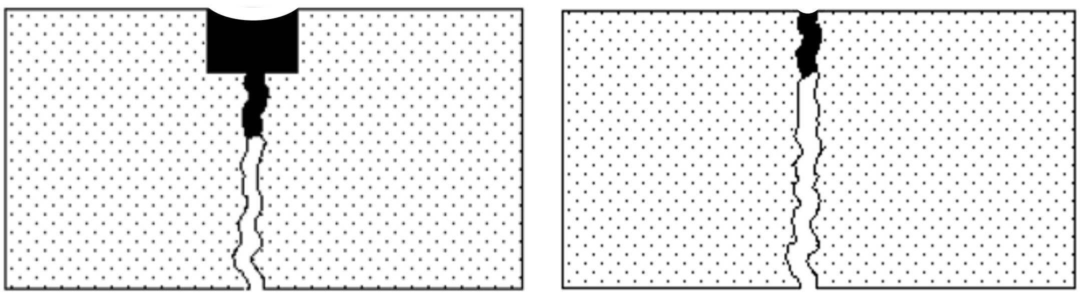
Crack sealing and filling refer to two different activities that can be performed on existing cracks in AC pavements, as described in the following sections:

- Crack sealing is the placement of an adhesive material into and over working cracks (i.e., those that open and close with temperature changes, such as transverse thermal and reflective cracks, diagonal cracks, and certain longitudinal reflective cracks) at the pavement surface in order to prevent the infiltration of moisture into the pavement structure. Successful crack sealing requires good crack preparation (i.e., routing or sawing a reservoir over the crack and power cleaning the reservoir) and the placement of high-quality, flexible materials (e.g., hot-poured elastomeric sealant or silicone products) into and possibly over the reservoir. As a stand-alone treatment, sealed cracks slow down or prevent surface water from infiltrating the pavement structure. This protects all layers from the damaging effects of moisture.

  Sealing cracks also prepares a pavement for the placement of other treatments, such as an overlay or a thin preservation application. When such primary treatments are planned and the types of cracks noted above are present, crack sealing slows down the rate of reflection cracking, reduces the severity of cracks that do reflect through, and provides additional waterproofing for those reflected cracks.
- Crack filling is very similar to crack sealing, with the primary difference being that the adhesive material is placed into and over nonworking cracks. These are typically longitudinal cold-joint and reflective cracks, edge cracks, and distantly spaced block cracks that are not expected to undergo either horizontal or vertical movement due to changes in temperature or the application of traffic loads. Like crack sealing, crack filling

helps to seal the pavement surface to slow down or prevent the infiltration of moisture into the pavement structure and reinforce the adjacent pavement. Crack filling operations generally entail minimal crack preparation and the use of lower quality materials (such as cold-poured products), and thus filled cracks may not perform as well as sealed cracks. Crack filling is also used as a pavement preparation process prior to placing another treatment, such as a preservation surfacing or an overlay.

Figure 7.1 shows typical crack sealing and filling configurations.



(a) (b)

Figure 7.1. (a) Typical Routed and Sealed Crack Configuration and (b) Typical Crack Filled Configuration

Cracks that are good candidates for sealing or filling are less than 25 mm (1 in.) wide, and are not so numerous that a more extensive surface seal is more appropriate. Furthermore, the pavement should be in good enough condition that when the cracks are maintained there are not numerous additional pavement distresses that would allow water to infiltrate the pavement. Crack sealing and filling are effective and appropriate maintenance treatments to limit surface moisture infiltration when the overall pavement condition is good and the cracks that are present can be effectively sealed. Table 7.1 is an example of guidelines for the performance of crack sealing and filling.

Where there are wider cracks, experience has shown that sealant materials do not have the ability to provide effective long-term sealing. In such instances, localized patches or more extensive repairs are appropriate. Furthermore, where there are many cracks and they are wider than hairline, crack sealing is not effective and alternate strategies should be pursued. Figure 7.2a is a photograph of a pavement with transverse and longitudinal cracks that are good candidates for repair, while Figure 7.2b shows cracks that are too wide to effectively seal, and Figure 7.2c shows a pavement with too many cracks to effectively seal.

It may be necessary to monitor pavement performance and continue to seal cracks that occur after the initial sealing activity. Depending on the material, preparation method and quality, and overall pavement condition, sealants may remain effective anywhere from 1 to 5 years, or even longer (Decker 2014). However, where moisture infiltration is a concern, evaluating crack sealing effectiveness must take into consideration whether the sealant is well bonded to the sides of the crack since that is essential to keeping water out of the pavement structure.

(a) (b)

(c)

Figure 7.2. (a) Longitudinal and Transverse Cracks that Are Good Candidates to Seal, (b) Longitudinal and Transverse Cracks that are too Wide to Seal, and (c) a Pavement Which Had too Many Cracks for Sealing to be the Most Effective Treatment

Table 7.1. Criteria for Determining Whether to Seal or Fill Cracks (Truschke et al. 2014)

	Crack Treatment	
Crack Characteristics	**Crack Sealing**	**Crack Filling**
Width	5 to 19 mm (0.2 to 0.75 in.)	5 to 25 mm (0.2 to 1.0 in.)
Edge Deterioration (i.e., spalls, secondary cracks)	Minimal to None (≤ 25 % of crack length)	Moderate to None (≤ 50 % of crack length)
Annual Horizontal Movement	≥ 3 mm (1/8 in.)	< 3 mm (1/8 in.)
Type of Crack	Transverse Thermal Transverse Reflective Longitudinal Reflective Longitudinal Cold Joint	Longitudinal Reflective Longitudinal Cold Joint Longitudinal Edge Distantly Spaced Block

7.1.1.1.1. Material Selection

A range of materials is used for crack sealing and filling, with material selection dependent on a number of factors, including climate conditions (at the time of installation and during the life of the treatment), crack characteristics and spacing/density, traffic loadings, and material availability and cost. While cold-applied, emulsion-based sealers are available, most materials used for longer lasting sealing comply with either ASTM D6690 (*Standard Specification for Joint and Crack Sealants, Hot Applied, for Concrete and Asphalt Pavements*) or D5078 (*Standard Specification for Crack Filler, Hot Applied, for Asphalt Concrete and Portland Cement Concrete Pavements*). The ASTM D6690 material is further subdivided into four different material types (I through IV) based on the high and low temperatures to which the pavement will be typically exposed. The FHWA's LTPPBind software can be used to determine the temperature inputs for any location in the United States.

7.1.1.1.2. Construction Process

Extensive information is available on the successful sealing and filling of cracks on flexible pavements (e.g., Smith and Romine 1999, Decker 2014, Truschke et al. 2014). The following general steps outline the process:

1. Perform routing operation (for sealing only).
2. Remove vegetation.
3. Clean with compressed air.
4. Dry (if crack is wet) with a hot-air lance.
5. Place material following manufacturer's or other recommendations, with proper consideration of configuration (e.g., recessed, overband, flush fill), finishing, blotting, and opening to traffic.

The FHWA also has available a checklist for crack seal construction (FHWA 2019), which may be downloaded at: https://www.fhwa.dot.gov/pavement/preservation/ppcl00.cfm.

7.1.1.2. Patching

Pavement patching is the repair of potholes, deterioration around cracks, delaminations, deteriorated patches, and other localized failures or defects of AC pavement surfaces. Patching is a common maintenance activity and, in addition to improving ride and pavement safety by restoring surface integrity, patching can slow down subsequent pavement deterioration by reducing the locations where water enters a pavement structure. Candidates for pavement patching are seen in Figure 7.3.

(a) (b)

Figure 7.3. Defects Which are Good Candidates for Patching to Waterproof a Pavement Include (a) Surface Delaminations and (b) Potholes

Much has been written about the materials and procedures used to patch bituminous surfaces (see, for example, the *Synthesis* by McDaniel et al. 2014, or earlier work by Wilson and Romine 1999). Of special significance is the differentiation that is often made between temporary, short-term repairs such as throw-and-go, throw-and-roll, and spray patching, and more permanent or semi-permanent patching. While this topic is thoroughly addressed elsewhere, the long-term effectiveness of the patch should be an important consideration in limiting damage due to moisture. This suggests that the most appropriate material and procedure combination is that which maintains surface integrity the longest; it is most likely to use high quality repair materials (usually asphalt concrete) and rigorous repair methods (sawcut or jackhammer out deteriorated pavement, restore any damage to subsurface layers, tack exposed surfaces, and place and compact HMA patch material in multiple lifts if appropriate). The use of temporary repair materials or procedures is unlikely to be effective in providing long-term protection against pavement damage caused by moisture. Figure 7.4 shows (a) poor performance of temporary patches in a badly fatigued pavement and (b) the good performance of a properly constructed permanent patch.

(a) (b)

Figure 7.4. Temporary Patches Placed in a Fatigued Pavement (a) Providing No Protection Against Moisture Damage and a Properly Placed, Semi-permanent Patch (b) Providing a Better Moisture Barrier

Project selection should consider whether maintenance patching will achieve the goal of reducing moisture damage. A good candidate pavement is one in which there are a limited number of discrete failures that can be repaired by patching, and the remainder of the pavement is comparatively defect free. Patches placed in a pavement that is experiencing widespread deterioration and many localized failures will not contribute to an intact pavement surface. Similarly, patches placed in a pavement with extensive cracking are also unlikely to provide the desired long-term objective of reducing pavement damage caused by moisture, even if all of the patch-worthy defects are repaired.

In addition to stand-alone patches, patching is a recommended pretreatment before either the placement of a preservation treatment or an overlay. Even though such patches will be covered, lower quality materials or construction methods will reflect through thin surfacings and perform poorly.

7.1.2. Preservation Strategies

The FHWA's February 25, 2016 memorandum on highway preservation and maintenance defines pavement preservation as "work that is planned and performed to improve or sustain the condition of the transportation facility in a state of good repair. Preservation activities generally do not add capacity or structural value, but do restore the overall condition of the transportation facility" (Waidelich 2016). It is widely accepted that pavement preservation refers to the practice of applying treatments to pavements in good condition in order to keep them in that state.

While the spectrum of pavement preservation treatments provides a range of benefits, including enhanced surface characteristics and the provision of a protective barrier against asphalt aging, the preservation strategies of interest here are those thin surfacings that seal a pavement surface in order to delay or prevent water infiltration into the pavement structure. With the exception of the recycling strategies, these are "edge to edge" surfacings that can be used to effectively seal pavements with some cracking but otherwise in good condition.

Table 7.2 identifies categories of preservation treatments that will seal a pavement's surface. This is by no means an exhaustive presentation of preservation treatments that will protect against moisture damage, nor does it include all of the variants of preservation treatments. Its inclusion is merely intended to illustrate that there are many treatments that provide this benefit. Examples of the many references providing additional explanation of these treatments include Caltrans (2008) and Peshkin et al. (2011).

In addition to the many variations in the materials used and how these treatments are specified and constructed, they provide distinctly different benefits with respect to how well they are able to seal the surface against moisture damage. In general, the thicker treatments provide more protection of the underlying pavement and greater resistance to wear. Where cracking is minimal, nonstructural, and hairline or narrow, the thicker treatments will perform better. However, the flexibility of the surfacing is also important, especially where there are existing cracks or where the underlying pavement is weaker, and these cracks have the potential to reflect through to the new surface. In such instances, a more flexible treatment such as a chip seal will provide better waterproofing than a more rigid treatment such as a slurry seal or thin overlay. Recent innovations to increase the flexibility of slurry seals and microsurfacing include the use of softer base asphalts and the incorporation of fibers in the mixtures.

If a preservation treatment is determined to be an appropriate method to protect the underlying pavement against moisture damage, Table 7.3 may help to differentiate the applicability of different treatments.

Another important consideration in the selection of any surface treatment that will cover an existing asphalt concrete pavement is the stripping susceptibility of the existing pavement. An existing asphalt concrete pavement may be susceptible to stripping but show no signs of stripping because water which enters the pavement structure can either flow through or evaporate out. These surface treatments have the ability to significantly alter the flow of water through a pavement structure, and trapped moisture will accelerate stripping-related damage in susceptible materials. Unless the existing materials are historically known to not have stripping problems, samples should be checked before the pavement is covered.

7.1.3. Drainage

The maintenance of drainage features on a pavement include consideration of the surface drainage conditions, the drainage ditch conditions, and the subsurface drainage conditions. *Surface drainage* refers to the ability of the pavement to shed water quickly so that it does not accumulate, which could otherwise lead to hydroplaning and wet weather accidents. *Drainage ditches* run parallel to the roadway and collect water to keep it from saturating the foundation layers. *Subsurface drainage* is installed on some pavements to more rapidly remove excess water from beneath the pavement to help minimize saturated conditions that could reduce the performance of the pavement. These are discussed individually in the following sections.

Table 7.2. Variations of Pavement Preservation Treatments which Seal the Pavement Surface and Provide a Barrier Against Moisture Intrusion

Treatment	Description	Common Variants	Treatment Life[1]
Scrub seal	Spray application of polymer-modified asphalt emulsion broomed into the surface, followed by spreading of fine aggregate (such as cubical sand), also broomed into surface. This treatment has minimal thickness.	Rejuvenating scrub seal	1 to 2 years
Chip seal	Spray application of binder (may be polymer or rubber-modified asphalt emulsion or hot-applied rubberized asphalt cement) followed immediately by spreading of chips. For a single chip seal, the total thickness is approximately the nominal maximum aggregate size (NMAS).	Single chip seal Double chip seal Sand seal	4 to 7 years
Slurry seal	Mixture of well-graded aggregate and asphalt emulsion (usually latex- or polymer-modified) applied to surface using a spreader box. Thickness ranges from 4 to 10 mm (0.15 to 0.375 in.)	Type I, II, and III	3 to 5 years
Micro surface	Mixture of well-graded, high-quality aggregate, mineral filler, and latex- or polymer-modified asphalt emulsion applied to the pavement surface using a spreader box. Typical thickness is 10 to 16 mm (0.375 to 0.625 in.)	Type II and III Double application Fiber reinforced	4 to 7 years
Cape seal	Chip seal application followed by a slurry or micro surface application. Thicknesses are equal to the sum of each application, which is typically 16 to 19 mm (0.625 to 0.75 in.)	Chip seal + slurry Chip seal + micro	4 to 8 years
Ultrathin bonded wearing course	Layer of gap-graded, modified HMA placed over a spray-applied, polymer-modified asphalt emulsion. Typical thicknesses are between 13 to 25 mm (0.5 and 1.0 in.)		4 to 10 years
Thin overlay	Thin overlays are HMA layers placed between 16 and 38 mm (0.63 and 1.5 in.) thick.	4.75 mm (0.19 in.) 9.5 mm (0.37 in.)	4 to 10 years
Surface recycling	Surface recycling techniques consist of the removal, mix modification, and reapplication of 25 to 102 mm (1 to 4 in.) of the pavement surface.	Hot in-place recycling Cold in-place recycling	5 to 10 years

[1] In this context treatment life should refer to the expected time during which the preservation treatment is providing protection against moisture damage. If the treatment is still in place, but cracks have reflected through and water is able to infiltrate into the pavement structure, the effectiveness of the treatment is compromised.

Table 7.3. Candidate Preservation Treatments Based on Type of Crack and Extent of Cracking

		Candidate Preservation Treatments			
		Type of Crack			
		Block	**Transverse**[1]	**Longitudinal/ Diagonal**[1]	**Fatigue/ Edge**[2]
Extent of Cracking	*High*	Surface Recycling	Surface Recycling[3]	Surface Recycling[3]	Not good candidate
	Moderate	Chip seal Cape seal Thin overlay Ultrathin bonded overlay Thin overlay	Chip seal Slurry seal Micro surface Cape seal Ultrathin Thin overlay	Chip seal Slurry seal Micro surface Cape seal Ultrathin Thin overlay	Chip seal
	Low	Scrub seal Slurry seal	Chip seal Slurry seal Micro surface Cape seal	Chip seal Slurry seal Micro surface Cape seal	Chip seal

[1] Preservation treatments for transverse, longitudinal, and diagonal cracking may perform better if the underlying cracks are first sealed.

[2] Fatigue cracking and edge cracking signifies pavement weakness that is not addressed by preservation treatments. For preservation treatments to be effective it must be determined that the overall pavement is strong enough to carry future loads and failed areas must first be patched. Because of its flexibility, a chip seal has the best chance of providing some moisture protection of an existing pavement exhibiting structural failure

[3] If cracking is top-down cracking, surface recycling may be used to remove cracking. For better resistance to moisture damage, the depth of cracking should be evaluated to determine if the recycling technique will remove the cracks.

7.1.3.1. Surface Drainage

All roadways must have an adequate cross slope to remove water from the roadway and thereby minimize the potential for hydroplaning. This is of particular importance at the ends of super elevated horizontal curves and at intersections. Key surface drainage characteristics include cross slopes, depth of ditches, and longitudinal grade of ditches. Table 7.4 summarizes general recommendations for these critical items.

Table 7.4. Cross Section and Surface Drainage Recommendations (Zimmerman et al. 2007)

Cross Section Feature	Recommendation
Pavement Surface Cross Slope	Minimum 2%
Shoulder Cross Slope	Minimum 3%
Width of Ditches	0.9 to 1.2 m (3 to 4 ft)
Depth of Ditches	Minimum 1.2 m (4 ft) beneath bottom of mainline pavement (deeper if greater flows anticipated)
Longitudinal Grade of Ditchline	Minimum 1%

Cross slopes and surface drainage may be compromised through rutting of the surface (Figure 7.5), through a buildup of materials along the shoulder that may impair lateral drainage (Figure 7.6), or through the application of multiple surface treatments over an extended period of time that has significantly altered the surface. It may also be that older pavements were constructed with an inadequate cross slope.

Figure 7.5. Water Collecting in Ruts of Asphalt Pavement

Figure 7.6. Water Ponding at Edge of Pavement (FHWA 2009)

For asphalt pavements, adequate cross slopes of the mainline pavement and shoulders can be achieved through milling, followed by the placement of an asphalt wearing course.

7.1.3.2. Drainage Ditches

Drainage ditches are an important element of a roadway, carrying water from the pavement and adjoining slopes to a discharge point. A well-maintained, smooth-flowing ditch will be free of heavy vegetation (e.g., tall grass, trees, cattails) and standing water, with enough grade to ensure self-cleaning and continuous flow (Smith 2006).

Drainage ditches are typically 0.9 to 1.2 m (3 to 4 ft) wide, have their low point 0.9 to 1.5 m (3 to 5 ft) below the bottom edge of the mainline pavement, and may be either vee-shaped or flat-bottomed (Figure 7.7). The vee-shaped ditches are easier to maintain with a grader, but the flat-bottomed ditches have a greater drainage capacity and are considered safer for errant vehicles that may leave the road. Because of the concern for the safety of errant vehicles, the sides of the ditches should be sloped 4:1 (horizontal:vertical) or flatter, although local conditions may not always allow this. Periodic cross drains or culverts are provided as part of the ditch drainage system to prevent excessive quantities of water being carried in the ditches. The size and shape of drainage ditches will depend largely on the amount of anticipated runoff and the type of soils on which the road is being built.

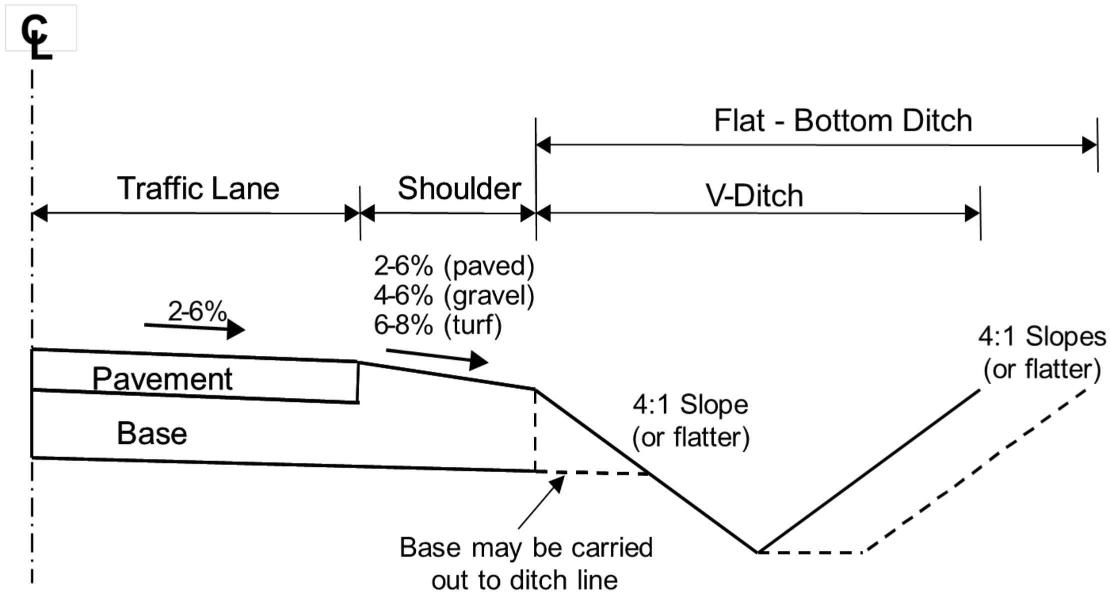


Figure 7.7. Recommended Pavement Cross Slopes and Drainage Ditch (Zimmerman et al. 2007)

A minimum longitudinal grade of 1 percent is desired for the ditches in order to prevent standing water. Longitudinal slopes greater than about 5 percent are not desirable because the steeper slopes can contribute to erosion of the ditch, unless the ditch is lined with rock to help minimize erosion potential.

The maintenance of the roadside ditch is critical to the effective drainage of the roadway. The ditch should be cleaned regularly to remove debris that could otherwise obstruct flow, and periodic blading may be needed to reestablish drainage capacity and longitudinal grades. Areas that exhibit repeated flooding may require deepening of the ditches in order to ensure that the outflow of water can be accommodated. Culverts should also be examined and cleaned to ensure that water is able to freely flow. All ditches, culverts, and other pavement drainage features should be regularly inspected, generally at least once a year (FHWA 1992).

In urban areas, a curb-and-gutter and drainage inlet system is often used to collect water into the storm sewer. The curb-and-gutter should be kept clean to allow unimpeded water flow and the inlets cleared of debris and silt.

7.1.3.3. Subsurface Drainage

Subsurface drainage systems (consisting of a permeable or free-draining base, longitudinal collector pipes, and outlet pipes) are used on some pavements as a more positive means of removing water from beneath the pavement structure. However, many of these drainage systems have been limited in their success because of clogging of the drain pipes or blocking of the outlets; this not only renders the drainage system ineffective but may also serve to keep the pavement in a more saturated state, potentially reducing performance. Some of the maintenance activities that should be performed are listed below (Christopher 2000; Smith and Hall 2001; Smith 2006):

- Inspection and monitoring (at least annually).
  - Examine condition of outlets.
  - Examine condition of roadway.
  - Inspect the pipe using optical video equipment (as needed).
- Preventive maintenance.
  - Clean and seal cracks and joints in the pavement to reduce moisture infiltration.
  - Install and maintain reference markers at outlet locations.
  - Clear debris and vegetation at outlets.
  - Maintain or replace rodent screens.
  - Flush and perform rodding of the edge drain system using high pressure equipment (as needed).
  - Clean ditches and reestablish depths and grades (as needed).
  - Regrade the shoulder to remove any buildup of dirt and debris that could otherwise prevent the lateral drainage of surface water from the mainline pavement.
- Repair.
  - Excavate and repair/replace damaged outlets or edgedrains.

With the availability of low-cost, small diameter, optical tube video cameras equipped with closed-circuit video systems, an inspection of edge drain systems can be done quickly and easily; any problem areas can be identified and located (see Section 6.3.2.2). Several agencies have adopted this technology for the inspection of edge drain systems on new pavement construction projects.

7.2. References

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CHAPTER 8. REHABILITATION TREATMENTS

8.1. Introduction

The need to address any moisture damage and drainage deficiencies should be determined as part of the pavement evaluation process. Existing distresses should be evaluated considering the role that moisture may have played in their development, and any signs of poor drainage (e.g., clogged outlets, standing water in the ditches) should be noted. Knowing this sort of information can help identify effective rehabilitation solutions to address moisture-related issues on asphalt and composite pavements.

8.2. Pavement Rehabilitation

Pavement rehabilitation includes treatments that provide structural enhancements that extend the service life of an existing pavement or improve its load carrying capacity. Rehabilitation techniques include restoration treatments and structural overlays. As described in Chapter 7, pavement maintenance and preservation activities include crack sealing/filling, patching, various thin surfacings, and in-place surface recycling, while rehabilitation activities are more substantial treatments such as asphalt and concrete overlays.

8.2.1. Treatment Type, Timing and Effectiveness

A summary of rehabilitation treatments for asphalt and composite pavements by distress type is provided in Table 8.1 and 8.2, respectively, along with the typical range of pavement life associated with each treatment.

Table 8.1. Rehabilitation Treatments Best Suited for Asphalt Pavement Distress (Adapted from Hall et al. 2001)

Distress	Asphalt Overlay	Concrete Overlay	Reconstruction
Fatigue cracking	✓	✓	✓
Block cracking	✓	✓	✓
Thermal cracking	✓	✓	✓
Slippage cracking	✓	✓	NA
Bleeding	✓	✓	NA
Rutting	✓	✓	NA
Shoving	NA	✓	✓
Weathering	✓	✓	NA
Raveling	✓	NA	NA
Stripping	✓	NA	✓
Potholes	NA	NA	✓
Bumps, settlements, heaves	✓	✓	✓
Typical Range in Service Life (years)	8 – 15	20 – 30	15 – 25 (asphalt) 20 – 30 (concrete)

Table 8.2. Rehabilitation Treatments Best Suited for Composite Pavement Distress (Adapted from Hall et al. 2001)

Distress	Asphalt Overlay	Asphalt Overlay of Fractured Slab	Unbonded Concrete Overlay	Reconstruction
Reflection cracking	✓	✓	✓	✓
Fatigue cracking	✓	✓	✓	✓
Punchout	✓	✓	✓	✓
Rutting	✓	NA	NA	NA
Shoving and corrugation	✓	NA	NA	NA
Stripping	✓	NA	✓	✓
Pumping	✓[1]	NA	✓[1]	✓
Pothole	✓	NA	✓	✓
"D" cracking	✓	NA	✓	✓
Typical Range in Service Life (years)	8 – 15	15 – 25	20 – 30	15 – 25 (asphalt) 20 – 30 (concrete)

[1] Includes subdrainage improvement.

8.2.2. Pretreatment Application Requirements

Depending on the level of existing distress, pretreatment applications may be required to ensure the expected service life (or level of performance) of the rehabilitation treatment is obtained. Pretreatments can range from inexpensive and quick treatment applications, such as crack sealing and crack filling, to more extensive, and typically more expensive treatments such as hot in-place recycling, cold in-place recycling, and full-depth reclamation. Table 8.3 provides a summary of pretreatment applications.

Table 8.4 and 8.5 include a summary of pretreatment, layer modification, applicability of asphalt and concrete for overlays and reconstruction, and drainage improvements based on distress type for asphalt and composite pavements, respectively.

For pavements with extensive deterioration, subdrainage modification (e.g., deepening roadside ditches, installation of retrofitted edgedrains, new or replacement of existing drainage system) may be required to ensure the intended rehabilitation service life is obtained (ARA 2004).

Table 8.3. Summary of Pretreatment Applications (Adapted from AASHTO 2015)

Treatment	Objective	Considerations
Crack or Joint Sealing	• Prevent moisture from entering pavement through cracks/joints. • Reduce further deterioration.	• Use for working cracks. • Preferably for crack widths less than 13 mm (0.5 in.). • Requires crack preparation. • Use higher quality sealant material.
Crack Filling	• Prevent moisture from entering pavement through cracks. • Reduce further deterioration.	• Use for nonworking cracks. • Preferably for crack widths less than 25 mm (1.0 in.). • Generally, only remove debris prior to crack filling. • Can use lower quality sealant materials.
Partial- and Full-Depth Repair	• Remove localized distress.	• Ensure repair limits extend beyond visible distress. • Ensure adequate compaction.
Thin Asphalt Leveling Course	• Improve ride. • Fill minor rutting. • Address slope and cross-slope issues.	• Confirm relationship between maximum aggregate size and lift thickness. • Apply tack coat prior to placement. • Ensure sufficient compaction due to quick cooling of thinner lift.
Asphalt Pavement Milling	• Remove an uneven longitudinal profile. • Remove rutting. • Provide surface texture for unbonded concrete overlay. • Remove existing asphalt pavement for partial- and full-depth repair.	• Ensure desired grades are obtained. • Thoroughly broom surface. • Remove loose material. • Apply sufficient tack coat material.
Hot In-Place Recycling	• Remove cracking. • Remove rutting. • Improve smoothness. • Upper 51 mm (2 in.) (typically) of the asphalt surface layer. • Adds some structural benefit.	• Consider variability of material properties of layer to be recycled. • Requires mix design to determine quantities of new materials and additives.
Cold In-Place Recycling	• Remove cracking. • Remove rutting. • Improve smoothness. • Upper 102 mm (4 in.) (typically) of the bituminous pavement. • Adds some structural benefit.	• Consider variability of material properties of layer to be recycled. • Requires mix design to determine quantities of new materials and additives.
Full-Depth Reclamation	• Pulverize and blend existing asphalt, base, subgrade layers into an upgraded, homogenous base layer.	• Thickness generally ranges from 102 to 305 mm (4 to 12 in.). • Stabilizing additives (e.g., lime, cement).

Table 8.4. Techniques for Mitigating Moisture Damage–Rehabilitation–Asphalt Pavements (Hall et al. 2001; AASHTO 2015)

Distress Type	Damage Condition	Pretreatment[1]	Layer Modification[2]	Overlay[2,3,4]	Reconstruct[2]	Improve Drainage
Fatigue Cracking	Base failure	Full-depth repair	Cold in-place recycle Full-depth reclamation	Asphalt overlay Concrete overlay	Asphalt Concrete	Install new or replace existing drainage Reconstruct shoulders
	Stripping	Partial- or full-depth repair	Milling Hot in-place recycle	Asphalt overlay Concrete overlay	Typically not required if only distress	Typically not required if only distress
	Freeze-thaw damage	Requires more extensive treatment	Cold in-place recycle Full-depth reclamation	Asphalt overlay Concrete overlay	Design for freeze-thaw conditions Asphalt Concrete	Install new drainage system Reconstruct shoulders
Transverse Cracking	Climate-related distress	Crack sealing or filling Partial- or full-depth repair	Milling Cold in-place recycle Full-depth reclamation	Asphalt overlay Concrete overlay	Typically not required if only distress	Typically not required if only distress
	Reflection cracking	Crack sealing or filling Partial- or full-depth repair	Milling Cold in-place recycle Full-depth reclamation	Asphalt overlay Concrete overlay	Typically not required if only distress	Typically not required if only distress
Raveling and Weathering	Low asphalt content mix, low mix density	Partial- or full-depth repair Thin asphalt overlay	Milling Hot in-place recycle	Asphalt overlay Concrete overlay	Typically not required if only distress	Typically not required if only distress
Rutting	Unstable mix	Requires more extensive treatment	Milling Hot in-place recycle	Asphalt overlay Concrete overlay	Typically not required if only distress	Typically not required if only distress
	Studded tire wear	Thin asphalt leveling course	Milling Hot in-place recycle	Asphalt overlay Concrete overlay	Typically not required if only distress	Typically not required if only distress
	Base or subgrade failure	Full-depth repair	Cold in-place recycle Full-depth reclamation	Asphalt overlay Concrete overlay	Asphalt Concrete	Typically not required if only distress
Potholes	Debonding of asphalt layers	Partial- or full-depth repair	Milling Hot in-place recycle	Asphalt overlay Concrete overlay	Typically not required if only distress	Not required if only distress
Ponding Water	Improper cross slope or inadequate drainage	Thin asphalt leveling course	Not applicable	Asphalt overlay Concrete overlay	Typically not required if only distress	Install new or replace existing drainage Reconstruct shoulder

[1] Localized distress only; depending on the severity and extent of the distress a more extensive treatment may be needed for long-term performance and cost effectiveness.

[2] Design and construct asphalt layers to minimize moisture susceptibility.

[3] Pretreatment and layer modification may be required in addition to the overlay.

[4] Pretreatment for bonded concrete overlays includes repair of potholes, localized moderate to severe fatigue cracking, and base and subgrade loss of support, and surface milling should be minimized so as to not reduce structural thickness (Harrington and Fick 2014). Pretreatment for unbonded concrete overlays includes remove and replace base and subgrade failures and variable asphalt strength, potholes should be filled, mill shoved and rutted asphalt ≥ 51 mm (2 in.), and fill cracks with crack widths ≥ maximum coarse aggregate size (Harrington and Fick 2014).

Table 8.5. Techniques for Mitigating Moisture Damage–Rehabilitation–Composite Pavements (Hall et al. 2001; AASHTO 2015)

Distress Type	Damage Condition	Pretreatment[1]	Layer Modification[2]	Overlay[2,3,4]	Reconstruct[2]	Improve Drainage
Fatigue Cracking	Concrete slab failure	Full-depth repair	Not applicable	Asphalt Concrete	Asphalt Concrete	Typically not required if only distress
	Stripping	Partial- or full-depth repair	Milling Hot in-place recycling	Asphalt Concrete	Typically not required if only distress	Typically not required if only distress
Transverse Cracking	Reflection cracking	Crack sealing or filling Full-depth repair	Milling	Asphalt Concrete	Typically not required if only distress	Install new or replace existing drainage
	"D" Cracking	Full-depth repair	Not applicable	Not applicable	Asphalt Concrete	Install new or replace existing drainage
Raveling or Weathering	Low mix asphalt content, low mix density	Partial- or full-depth repair	Milling Hot in-place recycling	Asphalt Concrete	Typically not required if only distress	Typically not required if only distress
Rutting	Unstable mix	Requires more extensive treatment	Milling Hot in-place recycling	Concrete	Typically not required if only distress	Typically not required if only distress
	Studded tire wear	Thin asphalt overlay	Milling Hot in-place recycling	Asphalt Concrete	Typically not required if only distress	Typically not required if only distress
Potholes	Punchout (CRCP only)	Requires more extensive treatment	Requires more extensive treatment	Not applicable	Asphalt Concrete	Typically not required if only distress
	Debonding of asphalt layers	Partial- or full-depth repair	Milling Hot in-place recycle	Asphalt Concrete	Typically not required if only distress	Typically not required if only distress
Ponding Water	Improper cross slope or inadequate drainage	Thin asphalt overlay	Requires more extensive treatment	Asphalt Concrete	Typically not required if only distress	Install new or replace existing drainage Reconstruct shoulder

[1] Localized distress only; depending on the depth and the extent of distress a more extensive treatment is needed for long-term performance and cost effectiveness.

[2] Asphalt layers designed and constructed to minimize moisture susceptibility.

[3] Pretreatment and layer modification may be required in addition to the overlay.

[4] Pretreatment for bonded concrete overlays includes repair of potholes, localized moderate to severe fatigue cracking, base and subgrade loss of support, and milling to achieve uniform bonding (Harrington and Fick 2014). Pretreatment for unbonded concrete overlays includes remove and replace base and subgrade failures and variable asphalt strength, potholes should be filled, mill shoved and rutted asphalt ≥ 51 mm (2 in.), full-depth repair of reflection cracking from faulting or panel tenting, and fill cracks with crack widths ≥ maximum coarse aggregate size (Harrington and Fick 2014).

8.2.3. Techniques for Mitigating/Addressing Reflective Cracking

Reflection cracking may occur in an asphalt overlay of an existing asphalt, concrete, or composite pavement due to the movement of the underlying pavement. Reflection cracking can result from both traffic and environmentally induced causes. Figure 8.1 provides an illustration of the mechanisms of reflection cracking.

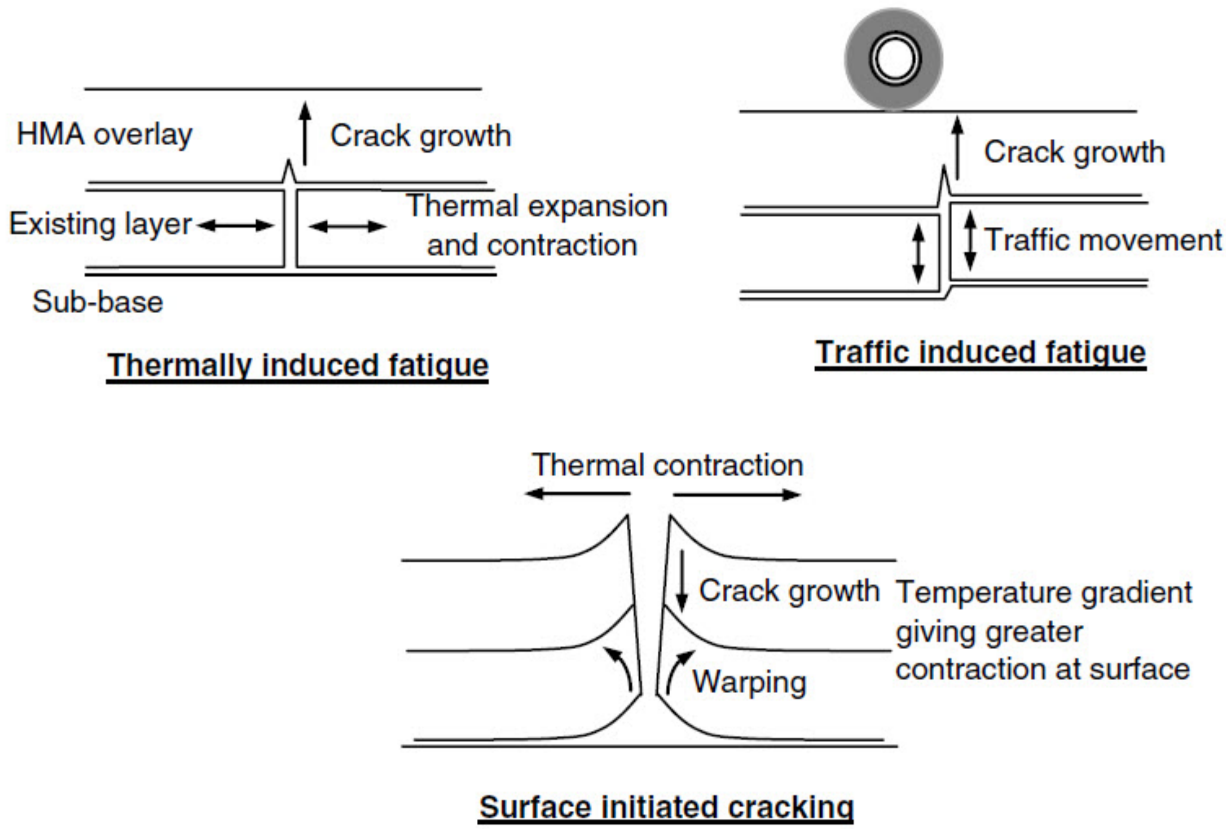


Figure 8.1. Reflection Cracking Mechanisms (Lytton et al. 2010)

In order to mitigate reflection cracking, it is important to identify and select an appropriate treatment method based on the site conditions (e.g., climate, traffic) and the condition of the existing pavement. A summary of treatments for mitigating reflection cracking of existing asphalt and concrete pavements is provided in Table 8.6.

Table 8.6. Summary of Methods for Mitigating Reflection Cracking (Adapted from Von Quintus et al. 2009)

Pavement Type	Treatment	Discussion
Existing asphalt pavements	Full-depth reclamation	• Effective technique when severe fatigue cracking is present.
	Heater scarification	• Limited to cracks confined to the wearing course.
	Hot in-place recycling	• Limited to cracks confined to the wearing course.
	Stress absorbing membrane interlayer	• Slows the rate of reflection cracking. • Requires adequate structural support. • Successful when crack width is narrow. • Creates a moisture barrier.
	Cushion course	• Increases layer thickness. • Potential issues with maintaining clearances.
	Thicker overlays	• Use in combination with other mitigation techniques.
Asphalt mixture modification	Asphalt rubber-modified mix	• Applicable in mild to moderate climates. • Design mixtures with proper strength/stability.
	Polymer modified asphalt	• Use in combination with other mitigation techniques.
	Stone matrix asphalt	• Use in combination with other mitigation techniques.
Asphalt overlay reinforcement	Geogrids	• Requires adequate strength for asphalt pavements. • Requires limited structural distress in concrete pavements.
	Geosynthetics	• Requires adequate strength for asphalt pavements. • Performs best on older asphalt pavements with narrow crack widths (< 3 mm [1/8 in.]). • Not applicable over wide (> 10 mm [3/8 in.]) transverse or shrinkage cracks in old asphalt pavements. • Not applicable on old concrete pavements.
Crack control	Saw and seal joints	• Concrete pavements without structural cracking and adequate support. • Must locate existing joints and saw cut asphalt overlay directly above joints.

The reflection cracking mitigation decision trees shown in Figure 8.2 through 8.4 were developed using previous research studies, forensic investigations, project surveys, and experience documented in the literature (Von Quintus et al. 2009). These figures include treatments for addressing reflective cracking prior to an asphalt overlay application for existing concrete pavement, existing asphalt pavements with an asphalt layer thickness less than 152 mm (6 in.), and existing full-depth asphalt pavements, respectively.

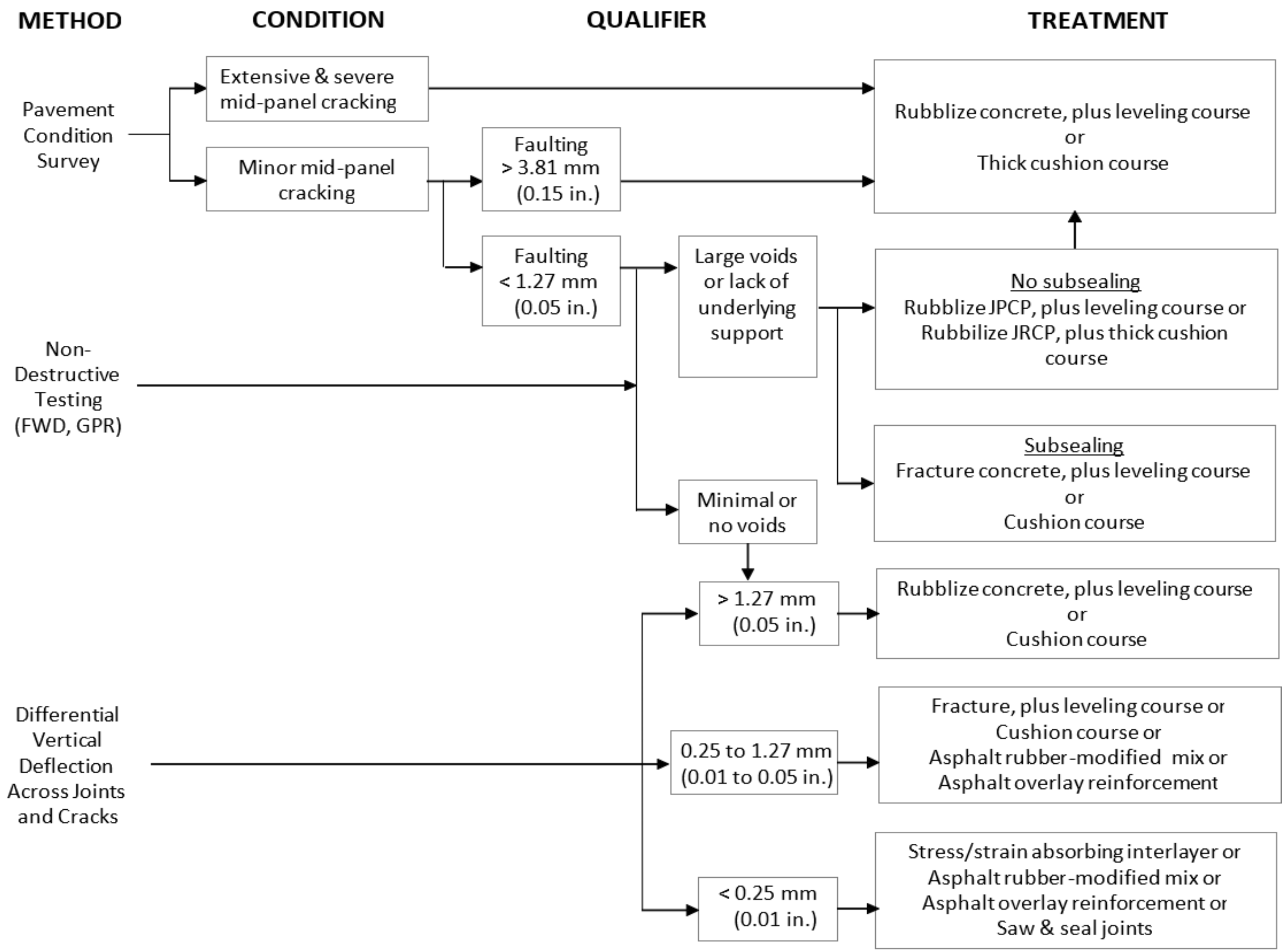


Figure 8.2. Reflection Cracking Control–Existing Concrete Pavement (Adapted After Von Quintus et al. 2009)

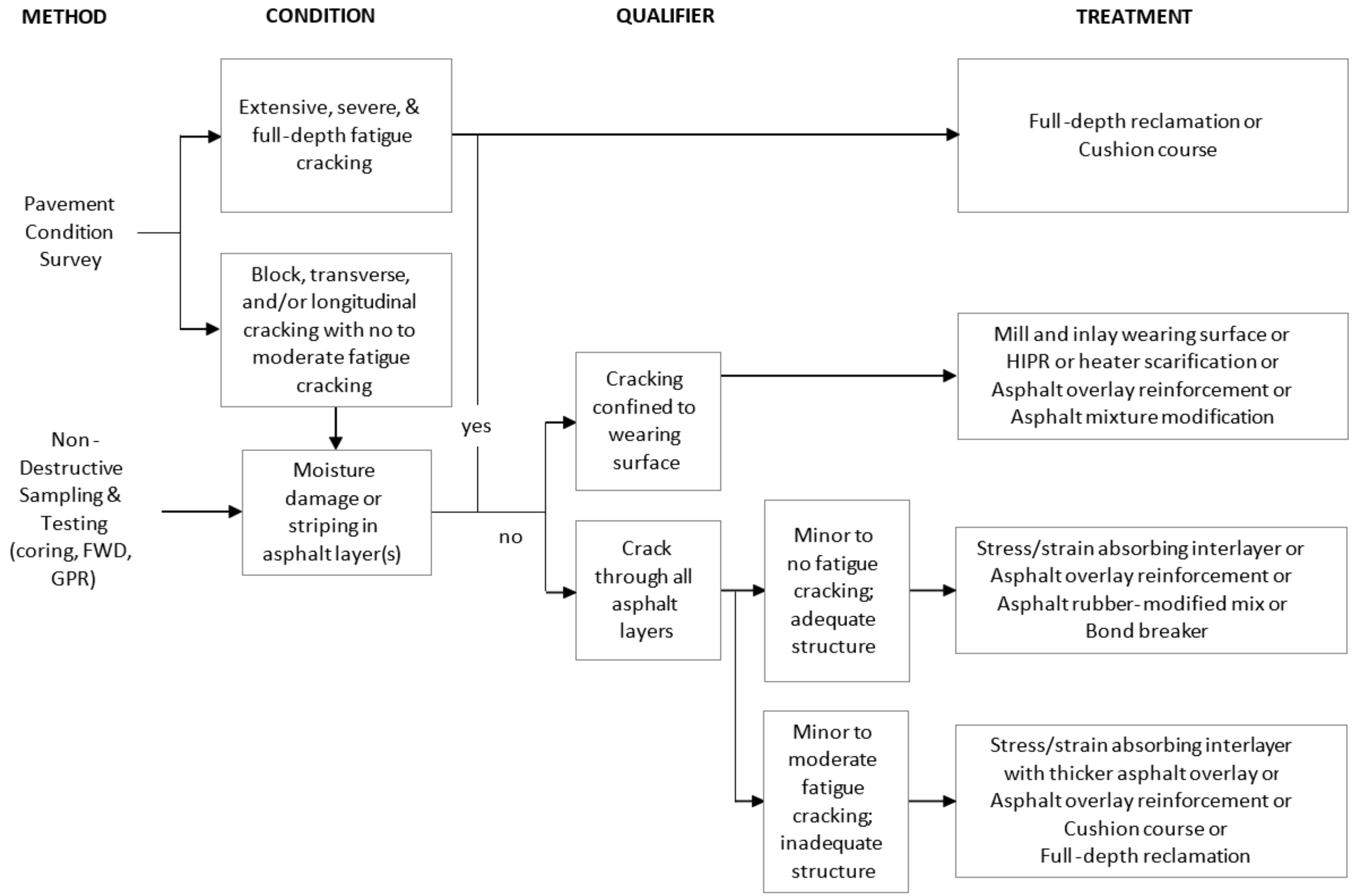


Figure 8.3. Reflection Cracking Control–Existing Asphalt Pavement–Asphalt Thickness < 152 mm (6 in.) (Adapted After Von Quintus et al. 2009)

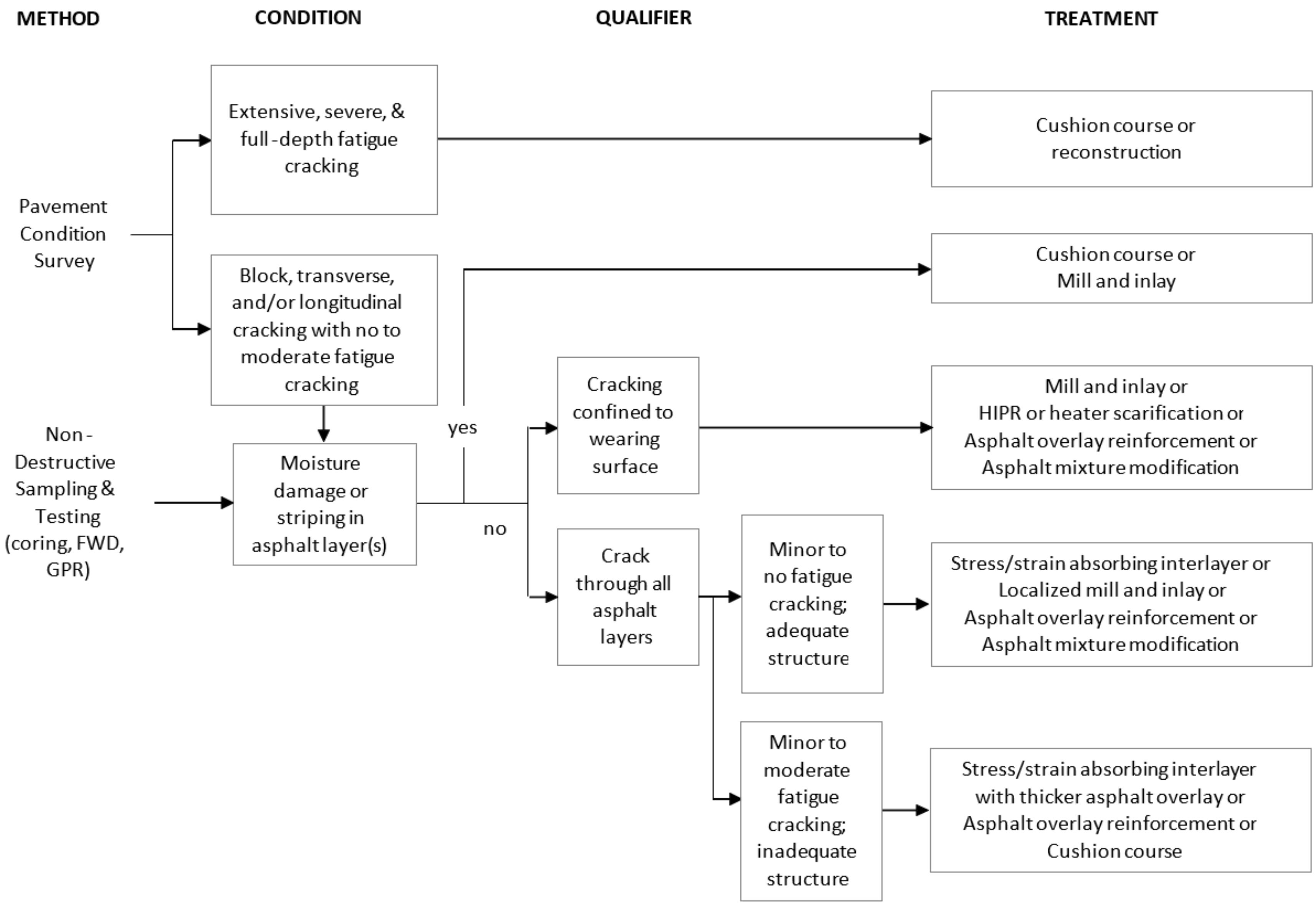


Figure 8.4. Reflection Cracking Control–Existing Full-Depth Asphalt Pavement (Adapted After Von Quintus et al. 2009)

8.2.4. Construction Considerations

As described in Chapters 5 and 6, selecting appropriate materials, conducting applicable asphalt mix designs, and ensuring proper construction techniques are essential activities for obtaining expected performance lives on rehabilitation treatments. The same level of effort in material selection, mix designs, and construction specifications should be applied during rehabilitation treatment application.

8.3. Drainage Rehabilitation

During the design phase of the pavement rehabilitation project, it is important to assess the need for new or additional drainage features. The following process may be used to assess drainage needs on pavement rehabilitation projects (ARA 2004):

1. **Assess drainage needs**—Conduct a pavement condition survey to determine the presence of moisture-related distress or moisture-accelerated distress. Additional assessment may include the presence of standing water, inadequate cross slopes, shallow ditches, vegetation at pavement edge, or vegetation clogging the existing drainage system.
2. **Determine drainage improvement alternatives**—Standing water conditions due to, for example, inadequate side slopes and ditches or debris and cattails in the side ditches, may be addressed by deepening of the roadway ditches. However, if drainage concerns require more extensive alternatives, retrofitted edgedrains (when viable, see Section 8.3.1), replacement of the existing drainage system, or a new drainage system may be warranted.
3. **Conduct hydraulic design**—The hydraulic design for new or reconstructed drainage systems is described in Chapter 4. The hydraulic design for edgedrains is described in Section 8.3.1.
4. **Develop pavement cross section**—Prepare a detailed cross section of the pavement structure, including hydraulic design assumptions and drainage features.

8.3.1. Retrofitted Edgedrains

Retrofitted edgedrains are designed and constructed for placement along the edge of pavement and are intended to drain water from the base (and subbase) layer(s) of the pavement structure. Examples of viable candidates for retrofitted edgedrains are listed below (ARA 2004):

- Moisture-related issues, such as the presence of water from spring thaw.
- Moisture-related distresses, such as stripping in the asphalt pavement layer(s) and pumping and D-cracking in concrete pavement layers.
- Pavement was constructed in a cut section location in a wet climate.
- Other signs of poor drainage, such as standing water in cracks, joints, and ditches.

Retrofitted edgedrains are not suitable for base or subbase materials with excessive fines (more than 15 percent passing the No. 200 sieve). Base materials with excessive fines may lead to clogging of the edgedrain system and significant base erosion (ARA 2004). Viable retrofitted edgedrain options are shown in Figure 8.5.

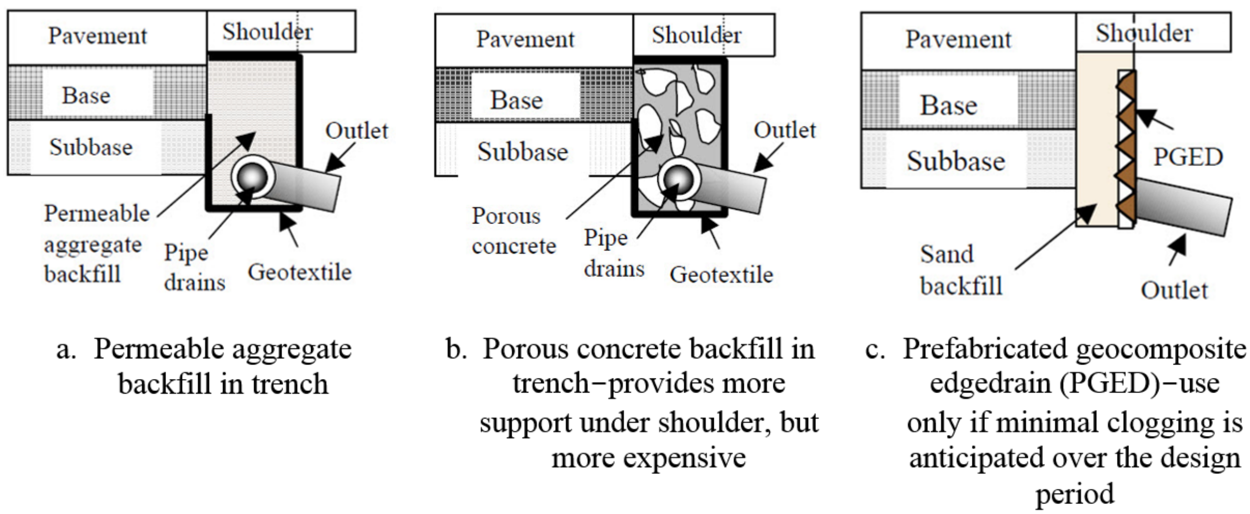


Figure 8.5. Retrofit Edgedrains for Rehabilitation (ARA 2004)

It should be noted that research conducted on highway rehabilitation projects in Virginia and Ohio (Elfino et al, 2000) concluded that the PGED (as shown in Figure 8.5c) should be located adjacent to the pavement layers to provide for quicker and more effective water removal. Virginia DOT adopted this practice and incorporated it into its road and bridge standards (see Figure 8.6).

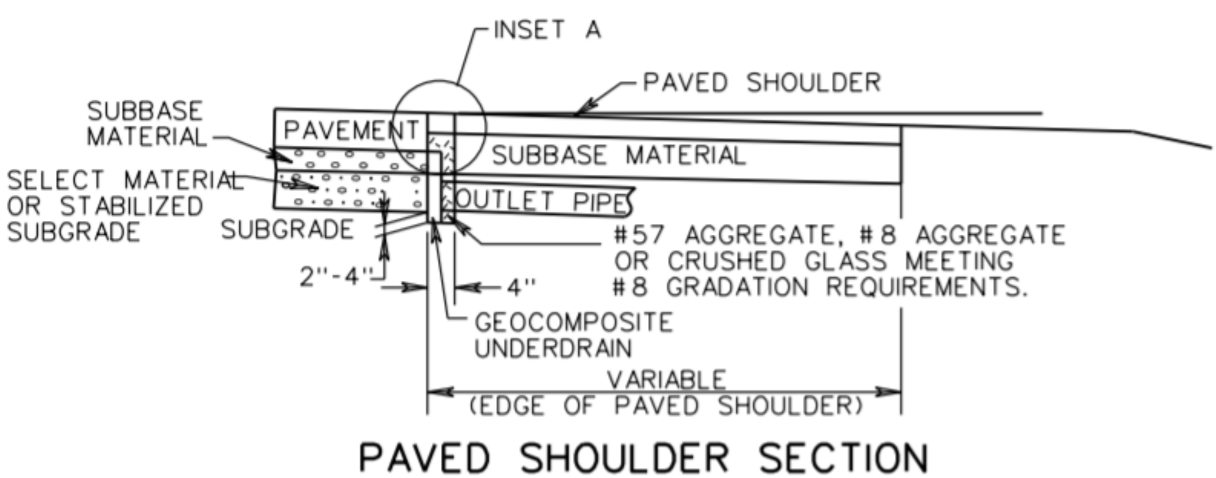


Figure 8.6. PGED Installation Configuration Used by Virginia DOT (VDOT 2016)

The edgedrain hydraulic design includes the following four-step process (ARA 2004):

1. **Determine the design flow for pipe capacity and outlet spacing**—The pavement infiltration discharge rate is determined using Equation 8.1.

$$q_i = I_c\left[\frac{N+1}{W} + \frac{1}{C_s}\right] \quad \text{Eq. (8.1)}$$

where

q_i = pavement infiltration rate, m^3/day/m,
I_c = crack infiltration rate, typically 0.223 m^3/day/m,
N = number of lanes,
W = pavement width, m, and
C_s = transverse crack spacing, m.

2. **Determine the edgedrain flow capacity**—For pipe edgedrains, use Equation 8.2 and for prefabricated geocomposite edgedrains use Equation 8.3 (see also Figure 8.7).

$$Q_p = \frac{0.2693\times10^{-3}}{n} D^{2.67} S^{0.5} \quad \text{Eq. (8.2)}$$

where

Q_p = pipe capacity, m^3/day,
n = Manning's roughness coefficient (0.012 for smooth pipes and 0.024 for corrugated pipes),
D = pipe diameter, mm, and
S = longitudinal slope, m/m.

$$Q_g = CD\left(S + \frac{D_1 - D_2}{L}\right)^{0.5} \quad \text{Eq. (8.3)}$$

where

Q_g = geocomposite edgedrain capacity, m^3/day,
C = manufacturer prefabricated geocomposite edgedrain (PGED) flow factor, m^3/day/m (typically 0.5 to 2.5),
D = average depth of flow,
D_1 = depth of flow zone, m,
D_2 = depth of outlet (outlet pipe diameter), m,
S = longitudinal slope, m/m, and
L = outlet spacing, m.

3. **Determine outlet spacing**—This can be accomplished using Equation 8.4.

$$L \leq \frac{Q}{q_i} \quad \text{Eq. (8.4)}$$

where

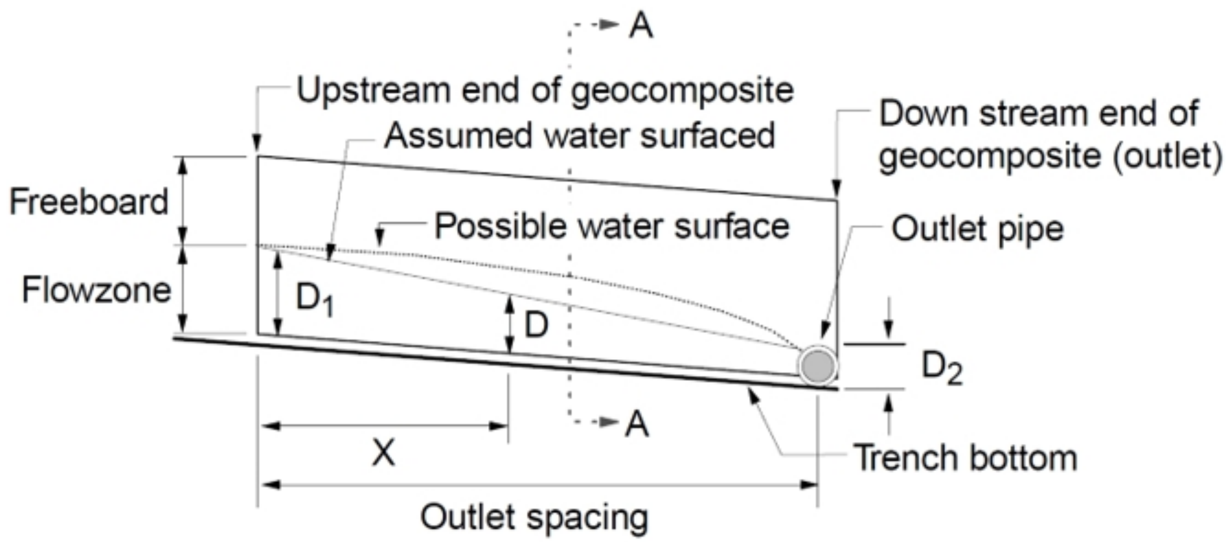
L = outlet spacing, m,
Q = pipe or PGED flow capacity, m^3/day, and
q_i = pavement infiltration rate, m^3/day/m.

4. **Determine the trench width**—The trench width should be sufficient to allow the unimpeded flow of water from the pavement structure into the trench. In general, if a permeable backfill material is used, the width needed for pipe installation should be sufficient to meet the hydraulic requirements (ARA 2004). Trench width is determined using Equation 8.5.

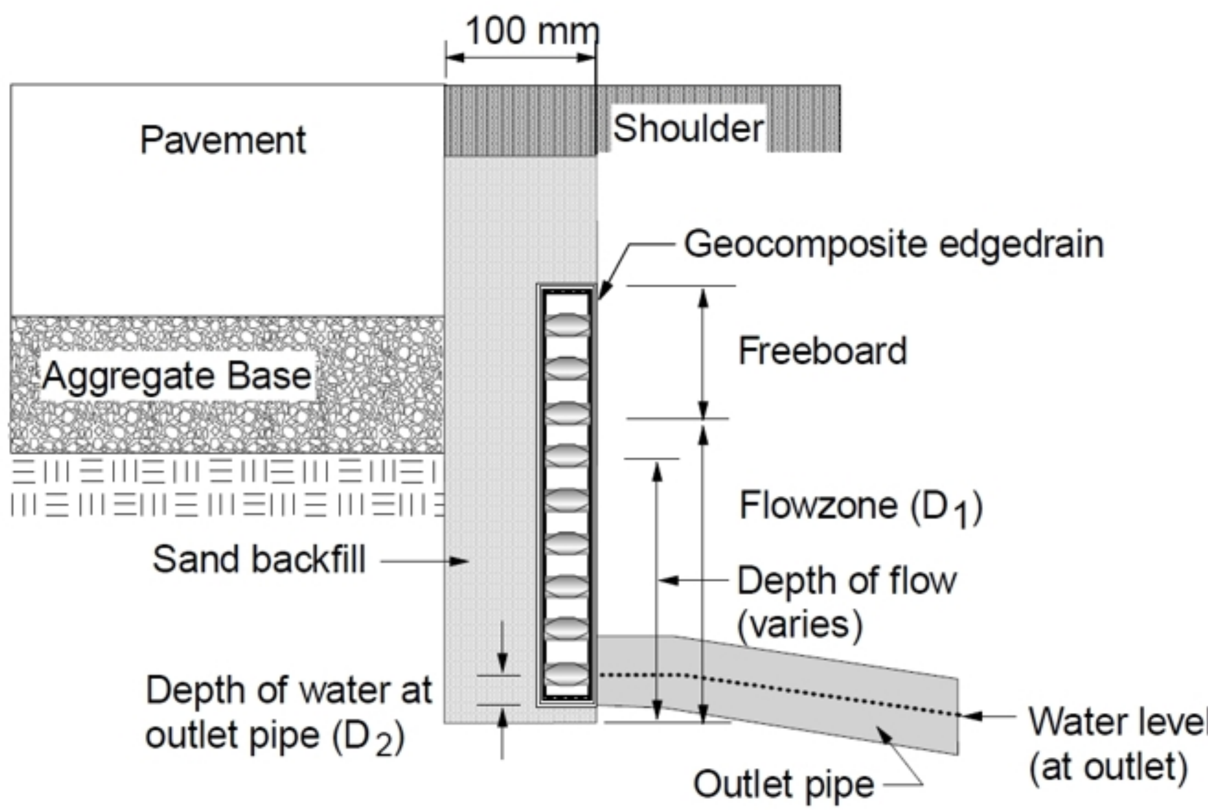
$$W_T \leq \frac{q_i}{k} \times 1000 \quad \text{Eq. (8.5)}$$

where

W_T = trench width, mm,
q_i = pavement infiltration rate, m^3/day/m, and
k = permeability of the backfill material, m/day.



a. Pipe outlet.



b. PGED cross section

Figure 8.7. Schematic of PGED Flow Capacity Variables (ARA 2004)

8.3.2. Shoulder Reconstruction

Reconstruction of the existing shoulders may be required due to existing conditions, pavement widening, replacement of an existing drainage system, or installation of a retrofitted edgedrain or new drainage system. Design and construction considerations for shoulder reconstruction are the same as those for new construction.

8.3.3. New or Replacement Drainage Systems

The design of new or replacement drainage systems are the same as for new construction as described in Chapter 4. The design and construction of a new or replacement drainage system should also take into consideration the existing pavement structure. Specific steps should be taken to ensure that the new or replacement drainage system provides a free flow of water from the pavement cross section into the drainage system.

8.3.4. Construction Considerations

Construction of retrofit edgedrains, pavement shoulders, and new or replacement drainage systems is the same as that used for new construction. For edgedrains, the minimum pipe diameters, connections, and outlet spacing are also the same as those used for new construction (ARA 2004).

8.4. Summary

This chapter provides a summary of the pretreatment applications and overlay recommendations for the rehabilitation of asphalt and composite pavements, methods for mitigating reflection cracking in asphalt and composite pavements, and drainage rehabilitation activities. In order to achieve long-term performance, it is important that proper pretreatment applications are selected, applicable overlay thicknesses are designed, and drainage conditions are investigated and appropriately addressed.

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CHAPTER 9. BENEFITS AND BARRIERS

9.1. Introduction

There is no single document that fully captures all available features, practices, and procedures for minimizing damage in asphalt and composite pavements due to the presence of water. In the absence of a readily available reference document providing that information, there is a greater risk that these pavements will exhibit reduced performance levels and increased preservation and rehabilitation costs.

This Guidelines document is intended to serve as resource that provides best practices for minimizing pavement damage due to the presence of water. A computer application (i.e., APP) and training materials provide additional resources to improve the practice of designing, building, maintaining, and rehabilitating flexible and composite pavements that are less susceptible to moisture damage.

9.2. Summary of Recommended Practices

Following is a summary of the recommended key practices for helping to address (or minimize) moisture damage in asphalt concrete or composite pavements.

9.2.1. Determine the Source(s) of the Moisture

When addressing a moisture problem in an existing pavement (or designing a new pavement to avoid moisture problems), it is important to identify the primary sources of moisture. If these sources are not identified, then there is an increased risk that the treatment(s) selected will be ineffective or the new design will be inadequate. For example, if a chip seal is applied to an existing asphalt concrete pavement to help prevent surface moisture from infiltrating the pavement, but the primary source of the moisture is from capillary action, then the chip seal will not address the moisture problem and the pavement will likely experience accelerated deterioration because of the unchecked moisture from below. In this particular case, the deterioration rate could be accelerated because the chip seal could trap subsurface moisture.

Chapter 2 of these Guidelines defines the primary sources of moisture on a pavement structure, including surface infiltration, capillary action and vapor movement, changes in depth of the water table, seepage from high ground, and infiltration from the edge, and emphasizes the importance of correctly identifying moisture sources on a particular project. It also describes how the moisture enters the pavement structure for each of these sources.

9.2.2. Identify the Key Mechanism(s) that are the Cause(s) of the Distress(es)

Along with determining the likely moisture sources for any given project, it is equally important to be able to identify the mechanisms by which moisture damage occurs. Armed with this information, engineers and roadway designers can develop more effective design or treatment options that address both the distress and the underlying cause. As an example, when the designer understands that frost heave occurs in the winter as ice forms into wet, frost-susceptible soils, the designer can develop a treatment plan that can 1) prevent moisture from entering the pavement, 2) reduce the depth of frost penetration, or 3) make the material less frost susceptible.

Chapter 3 provides basic descriptions for four different mechanisms that contribute to the different forms of moisture damage in an asphalt or composite pavement. These mechanisms include material softening/weakening, frost heave, asphalt stripping, and subsurface pumping. The chapter also provides a list of the common distress types associated with each mechanism.

9.2.3. Consider Design Features

Chapter 4 discloses three main approaches for controlling or limiting moisture damage in pavements: 1) preventing moisture from entering the pavement system, 2) quickly removing moisture after it enters the system, and 3) using materials and design features that are insensitive to the effects of moisture. For each of these approaches, there is at least one design feature that should be considered when developing solutions to address the prevailing drainage problem. These features are described under four different categories shown below (and described in Chapter 4).

- **Roadway geometric design**—By determining the right combination of geometric factors (e.g., cross slope, longitudinal slope, length of drainage path, and so on) for the pavement, shoulders, and curb and gutter, the pavement designer can come up with a geometric design for the pavement that minimizes the exposure of the pavement structure to moisture.
- **Subsurface drainage design**—A drainage system consisting of permeable layers, edge drains, underdrains, or horizontal drains, will help remove moisture entering the pavement from targeted sources before it significantly compromises the pavement structure. Most of these features can be considered as part of the design for either a new pavement construction or reconstruction project. Retrofitted edge drains can be considered as an option for a pavement rehabilitation project.
- **Pavement (structural) design**—To offset the weakening effect of prolonged moisture exposure in the pavement, it is often worth considering structural design alternatives that 1) increase the pavement's load-carrying carrying capacity, 2) make the pavement more resistant to the presence of moisture, or 3) help prevent moisture from entering the pavement. The primary structural design option described in these Guidelines is subgrade stabilization, which can be achieved through mechanical means (such as adding or blending gravel and the use of geosynthetics), through the use of additives (such as portland cement, lime, and lime fly ash), or through a selection of a higher quality base material. Other specific design considerations for asphalt pavements, composite pavements, and pavement surface type (i.e., dense-graded HMA, stone mastic asphalt, open-graded HMA, and various surface treatments) are also included.
- **Cold-climate design**—Methods are identified to combat the negative effects of moisture and frost penetration in cold climates, i.e., frost heave in winter and high moisture in spring. The methods include removing frost-susceptible soils and replacing them with non-frost-susceptible materials, stabilizing the subgrade soil, and increasing the structural capacity of the pavement.

9.2.4. Consider Available Materials

Chapter 5 provides detailed guidance and information on the selection of paving materials associated with the various design features described in Chapter 4. These materials and their related characteristics should be thoroughly considered when trying to correct or limit moisture damage in a pavement. Under the heading of pavement structure, these include base materials (unbound, aggregate separator, asphalt treated, asphalt treated permeable, cement treated, and cement treated permeable) and asphalt mixtures. In the category of geosynthetics, the primary materials are geotextiles and geocomposites. Finally, for drainage systems, the key materials covered are trench backfill, drain pipe, outlet pipe, headwalls, and geotextiles.

9.2.5. New Construction

The most cost-effective time to address the potential for a pavement to experience moisture damage is in the design and construction stage. Accordingly, Chapter 6 provides guidance on three topics associated with new pavement construction. The bulk of the guidance is on the individual layers of the pavement:

- Subgrade soil treatment requirements (identification of weak areas, removal and replacement methods, stabilization methods, and dewatering systems).
- Base placement and compaction requirements.
- Asphalt concrete placement and compaction requirements.
- Concrete construction requirements.
- Construction quality control and acceptance.

Two additional topics in Chapter 6 address the key issues associated with proper installation and construction monitoring of drainage systems and discuss the basic design considerations for roadway widening.

9.2.6. Maintenance and Preservation Strategies

Like other forms of pavement distress, the rate of damage associated with exposure to moisture can be significantly reduced by employing sound maintenance and preservation practices during the life of the pavement that will help keep water out. Chapter 7 addresses these practices from three different perspectives:

- **Maintenance strategies**—Patching and crack sealing/filling are the primary maintenance strategies used to address localized pavement distresses that can affect load-carrying capacity and ride quality, as well as moisture infiltration. Although these strategies are generally considered simple and straightforward, there are selection criteria, material considerations, and construction best practices that can improve their effectiveness.
- **Preservation strategies**— “Edge to edge” pavement surfacings or surface preservation treatments can help keep an existing pavement in good condition. In general, these treatments reduce the rate of age-hardening and improve surface friction. They also seal the pavement surface against moisture infiltration. Descriptive information and guidance are provided on seven types of surface preservation treatments appropriate for flexible

and composite pavements, including scrub seals, chip seals, slurry seals, microsurfacing, cape seals, ultrathin bonded wearing courses, and thin overlays.

- **Drainage**—When considering the maintenance needs of an existing pavement, it is also important to consider the maintenance needs of the pavement drainage features. For the purposes of these Guidelines, they are discussed in terms of surface drainage, drainage ditches, and subsurface drainage.

9.2.7. Rehabilitation Treatments

The selection of the right treatment for a rehabilitation project is much simpler than addressing drainage in new design. This is because most of the moisture damage problems will already be manifesting themselves as various forms of distress that can be identified and corrected. Chapter 8 of these Guidelines provides rehabilitation recommendations to address the needs of both existing pavements and existing drainage systems. For pavements, guidance is provided in the form of a) rehabilitation treatment selection based on the observed types of distress, b) pretreatment application requirements, c) techniques to address reflection cracking, and d) construction considerations. For drainage systems, recommendations are offered primarily for a) a stepwise process to assess the needs, and b) the design and construction of retrofitted edge drains. Reference to other parts of the Guidelines cover shoulder reconstruction, new or replacement drainage systems, and overall construction considerations.

9.3. Benefits of Implementation

These Guidelines provide a standard, uniform body of information that will help highway engineers and designers develop a better understanding of all the factors that contribute to moisture damage within a pavement; as such, they provide best practice recommendations for addressing potential moisture problems in new design, maintenance and preservation, and reconstruction. By implementing these best practice recommendations into everyday practice, highway agencies will experience fewer problems with moisture damage, improved performance, and lower long-term costs. These Guidelines will be especially beneficial for the engineers and designers new to pavement engineering.

To assist highway agencies with implementation and rapid deployment of these Guidelines, three tools were developed. The first is a stand-alone computer application that provides users with the means to access key information more efficiently. The second is a 1-hour webinar describing the Guidelines document, the computer application, and their use. The third is a 1-day training course that includes an instructor’s manual, a participant’s workbook, visual aids, and workshop exercises.

9.4. Potential Barriers of Practices and Features

None of the best practices recommended in these Guidelines are new or unique. Accordingly, the only real barriers to use throughout the country are informing highway agencies about the availability of the Guidelines and providing training/education in a manner that demonstrates that moisture damage is a major problem and encourages highway agency personnel that, where applicable, they should update their practices. The webinar, the training course, and the stand-alone application were all developed to support the implementation process.

9.5. Summary

With the increasing emphasis on improving pavement engineering practices to get the most out of taxpayer dollars, NCHRP Project 1-54 is a timely study. By developing comprehensive guidelines, incorporating them into a standard of practice, and providing needed training, this NCHRP project provides the tools that highway agencies and public works departments need to better address moisture problems in their pavements and realize better performing, longer lasting pavements.