

FINAL
CONTRACT REPORT
VTRC 09-CR2

COMPOSITE PAVEMENT SYSTEMS: SYNTHESIS OF DESIGN AND CONSTRUCTION PRACTICES

GERARDO W. FLINTSCH, Ph.D., P.E.
Director
Center for Safe and Sustainable Infrastructure
Virginia Tech Transportation Institute

BRIAN K. DIEFENDERFER, Ph.D., P.E.
Research Scientist
Virginia Transportation Research Council

ORLANDO NUNEZ
Graduate Research Assistant
Center for Safe and Sustainable Infrastructure
Virginia Tech Transportation Institute



Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 09-CR2	2. Government Accession No.:	3. Recipient's Catalog No.:	
4. Title and Subtitle: Composite Pavement Systems: Synthesis of Design and Construction Practices		5. Report Date: November 2008	
		6. Performing Organization Code:	
7. Author(s): Gerardo W. Flintsch, Ph.D., P.E., Brian K. Diefenderfer, Ph.D., P.E., and Orlando Nunez		8. Performing Organization Report No.: VTRC 09-CR2	
9. Performing Organization and Address: Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24061		10. Work Unit No. (TRAIS):	
		11. Contract or Grant No.: 85414	
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation Federal Highway Administration 1401 E. Broad Street 400 North 8th Street, Room 750 Richmond, VA 23219 Richmond, VA 23219-4825		13. Type of Report and Period Covered: Final Contract	
		14. Sponsoring Agency Code:	
15. Supplementary Notes:			
16. Abstract: <p>Composite pavement systems have shown the potential for becoming a cost-effective pavement alternative for highways with high and heavy traffic volumes, especially in Europe. This study investigated the design and performance of composite pavement structures composed of a flexible layer (top-most layer) over a rigid base. The report compiles (1) a literature review of composite pavement systems in the U.S. and worldwide; (2) an evaluation of the state-of-the-practice in the U.S. obtained using a survey; (3) an investigation of technical aspects of various alternative composite pavement systems designed using available methodologies and mechanistic-empirical pavement distress models (fatigue, rutting, and reflective cracking); and (4) a preliminary life cycle cost analysis (LCCA) to study the feasibility of the most promising composite pavement systems.</p> <p>Composite pavements, when compared to traditional flexible or rigid pavements, have the potential to become a cost-effective alternative because they may provide better levels of performance, both structurally and functionally, than the traditional flexible and rigid pavement designs. Therefore, they can be viable options for high volume traffic corridors. Countries, such as the U.K. and Spain, which have used composite pavement systems in their main road networks, have reported positive experiences in terms of functional and structural performance. Composite pavement structures can provide long-life pavements that offer good serviceability levels and rapid, cost-effective maintenance operations, which are highly desired, especially for high-volume, high-priority corridors.</p> <p>Composite pavements mitigate various structural and functional problems that typical flexible or rigid pavements tend to present, such as hot-mix asphalt (HMA) fatigue cracking, subgrade rutting, portland cement concrete (PCC) erosion, and PCC loss of friction, among others. At the same time, though, composite systems are potentially more prone to other distresses, such as reflective cracking and rutting within the HMA layer. Premium HMA surfaces and/or reflective cracking mitigation techniques may be required to mitigate these potential problems.</p> <p>At the economic level, the results of the deterministic agency-cost LCCA suggest that the use of a composite pavement with a cement-treated base (CTB) results in a cost-effective alternative for a typical interstate traffic scenario. Alternatively, a composite pavement with a continuously reinforced concrete pavement (CRCP) base may become more cost-effective for very high volumes of traffic. Further, in addition to savings in agency cost, road user cost savings could also be important, especially for the HMA over CRCP composite pavement option because it would not require any lengthy rehabilitation actions, as is the case for the typical flexible and rigid pavements.</p>			
17 Key Words: composite pavement, pavement type selection, semi-rigid pavement, mechanistic evaluation		18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.	
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 58	22. Price:

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Gerardo W. Flintsch, Ph.D., P.E.
Director, Center for Safe and Sustainable Infrastructure
Virginia Tech Transportation Institute

Brian K. Diefenderfer, Ph.D., P.E.
Research Scientist
Virginia Transportation Research Council

Orlando Nunez
Graduate Research Assistant
Center for Safe and Sustainable Infrastructure
Virginia Tech Transportation Institute

Project Manager: Brian K. Diefenderfer, Ph.D., P.E.

Contract Research Sponsored by
the Virginia Transportation Research Council

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
And the university of Virginia since 1948)

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

November 2008
VTRC 09-CR2

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Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. The contractor performs final editing and proofreading of the report.

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ABSTRACT

Composite pavement systems have shown the potential for becoming a cost-effective pavement alternative for highways with high and heavy traffic volumes, especially in Europe. This study investigated the design and performance of composite pavement structures composed of a flexible layer (top-most layer) over a rigid base. The report compiles (1) a literature review of composite pavement systems in the U.S. and worldwide; (2) an evaluation of the state-of-the-practice in the U.S. obtained using a survey; (3) an investigation of technical aspects of various alternative composite pavement systems designed using available methodologies and mechanistic-empirical pavement distress models (fatigue, rutting, and reflective cracking); and (4) a preliminary life cycle cost analysis (LCCA) to study the feasibility of the most promising composite pavement systems.

Composite pavements, when compared to traditional flexible or rigid pavements, have the potential to become a cost-effective alternative because they may provide better levels of performance, both structurally and functionally, than the traditional flexible and rigid pavement designs. Therefore, they can be viable options for high volume traffic corridors. Countries, such as the U.K. and Spain, which have used composite pavement systems in their main road networks, have reported positive experiences in terms of functional and structural performance. Composite pavement structures can provide long-life pavements that offer good serviceability levels and rapid, cost-effective maintenance operations, which are highly desired, especially for high-volume, high-priority corridors.

Composite pavements mitigate various structural and functional problems that typical flexible or rigid pavements tend to present, such as hot-mix asphalt (HMA) fatigue cracking, subgrade rutting, portland cement concrete (PCC) erosion, and PCC loss of friction, among others. At the same time, though, composite systems are potentially more prone to other distresses, such as reflective cracking and rutting within the HMA layer. Premium HMA surfaces and/or reflective cracking mitigation techniques may be required to mitigate these potential problems.

At the economic level, the results of the deterministic agency-cost LCCA suggest that the use of a composite pavement with a cement-treated base (CTB) results in a cost-effective alternative for a typical interstate traffic scenario. Alternatively, a composite pavement with a continuously reinforced concrete pavement (CRCP) base may become more cost-effective for very high volumes of traffic. Further, in addition to savings in agency cost, road user cost savings could also be important, especially for the HMA over CRCP composite pavement option because it would not require any lengthy rehabilitation actions, as is the case for the typical flexible and rigid pavements.

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INTRODUCTION

Transportation agencies and the road building industry have traditionally designed and constructed two pavement types, flexible and rigid. The selection of which type to use is often based on a pavement type selection (PTS) process to decide the best pavement alternative for a particular project. This process helps pavement engineers determine the most cost-effective pavement type capable of supporting anticipated traffic under existing environmental conditions and providing safety and driving comfort to the traveling public (VDOT, 2001).

Composite pavement systems have shown good potential for becoming a cost-effective pavement alternative for high volume roadways (Nunn et al., 1997; Nunn, 2004). There are several types of composite pavement structures; however, in this study, a composite structure is defined as a multi-layer structure where there is a flexible layer (top-most layer) over a rigid layer. The flexible (asphalt concrete) layer (e.g., dense-graded hot-mix asphalt [HMA], stone matrix asphalt [SMA], open-graded friction course [OGFC], etc.) provides a smooth, safe, and quiet driving surface, whereas the rigid layer (e.g., cement-treated base [CTB], roller-compacted concrete [RCC], continuously reinforced concrete pavement [CRCP], etc.) provides a stiff and strong base. This high modulus rigid base tends to change the traditional pavement concept in which the layers' moduli decrease as depth increases. In composite structures, the stiffness of the base (rigid layer) is greater than that of the surface layer (flexible layer).

Composite structures are also known as semi-rigid or flexible composite structures in other countries. These pavements have been widely used in roads where there is a high traffic volume (50+ million equivalent single axle loads [ESALs]), heavily loaded trucks (which translates to high ESALs), and the designer seeks long-life pavements with minimum

rehabilitation (such as replacement of the wearing surface) (Nunn, 2004; Jofre and Fernandez, 2004).

PURPOSE AND SCOPE

This project was designed to provide the Virginia Department of Transportation (VDOT) with a synthesis of current information regarding composite pavement systems. This report compiles (1) a literature review of composite pavement systems in the U.S. and worldwide, (2) an evaluation of the state-of-the-practice in the U.S. obtained through a survey, (3) an investigation of technical aspects of composite pavement systems using mechanistic analysis and mechanistic-empirical pavement distress models (fatigue, rutting, and reflective cracking), and (4) a study of the feasibility of composite pavement systems through a life cycle cost analysis (LCCA).

METHODS

This study consisted of four steps: the first step consisted of a literature review of composite pavement systems in the U.S. and worldwide, the second step included a survey of state pavement design engineers from state DOT's, the third step used mechanistic-empirical pavement distress models to study the response of composite pavement systems, and the final step investigated the feasibility of composite pavement systems by a life cycle cost analysis.

Literature Review

The literature review portion of this study was performed using available electronic databases including: Transportation Research Information Services (TRIS) bibliographic database, the catalog of Transportation Libraries (TLCat), the Catalog of Worldwide Libraries (WorldCat), the Transportation Research Board Research in Progress (RiP) and Research Needs Statements (RNS) databases.

Survey

A web-based survey was emailed to state DOT pavement design engineers during February 2008. Responses were received from 34 state agencies; 11 of which have experience designing composite pavement structures.

Mechanistic and Mechanistic-Empirical Evaluation

Mechanistic analysis of various composite pavement structures was performed using software assuming both non-linear and linear-elastic pavement behavior. The software allowed for the pavement behavior to be analyzed. In addition, empirical-based deterioration models were used to assess the anticipated condition of the analyzed structures.

Life-Cycle Cost Analysis

A life-cycle cost analysis was performed, following VDOT guidelines, to evaluate the feasibility of composite pavement systems and to estimate their cost-effectiveness.

BACKGROUND

Composite pavements have been studied for many years. They are known as semi-rigid pavement structures (NCHRP, 2004), premium composite pavements (Von Quintus, 1979; Hudson and Roberts, 1981), long-life pavements (Nunn et al., 1997), and flexible composite pavements (Nunn, 2004).

A composite pavement structure is defined as a structure comprising two or more layers that combine different characteristics and that act as one composite material (Smith, 1963). The two most commonly used materials that compose this composite structure are a flexible layer (e.g., HMA) and a rigid layer (e.g., PCC, cement-treated base [CTB], cement stabilized base [CSB], rolled-compact concrete [RCC], or lean mix concrete). There is no single definition applicable to composite pavements because an HMA overlay on a CTB can be considered a composite pavement; likewise, a thin PCC overlay on an HMA layer, known as whitetopping, has also been considered a composite pavement. Furthermore, a PCC surface layer applied on top of another PCC layer before the bottom layer has set may be considered a composite “wet on wet” pavement. In this study, the composite pavement system investigated was a rigid base overlaid with a flexible layer as shown in example cross-sections in Figure 1.



Figure 1. Typical Cross-sections of Composite Pavements

Composite pavements, when compared to traditional flexible or rigid pavements, have the potential to provide better levels of performance both structurally and functionally (technical aspects) while being an economically viable alternative to the traditional flexible and rigid

pavement designs (economic aspect). Some of the general benefits that composite pavements can provide are (Donald, 2003; Jofre and Fernandez, 2004; Nunn, 2004):

- Strong support to the flexible layer provided by the rigid base layer
- Good levels of the rideability of the pavement and driver comfort by providing a smooth and quiet driving surface
- Adequate pavement surface friction properties
- Preservation of the structural integrity of the rigid base provided by an asphalt surface layer, which can be periodically replaced
- Prevention of the intrusion of deicing salts and surface water to the rigid base due to the protection provided by the asphalt layer
- Reduction of the temperature gradient in the rigid layer because of the insulation provided by the overlying asphalt surface layer.

Potential Benefits

Donald (2003) discusses how the traditional heavy-duty pavement type is a thick asphalt pavement placed on an unbound aggregate base and granular subbase course. This type of conventional flexible pavement structure relies principally on the HMA for stiffness as the HMA is the layer that provides the majority of the structural capacity. Therefore, tensile strains at the bottom of the HMA layer need to be analyzed when designing a flexible pavement as shown in Figure 2a. This means that the risk of fatigue cracking (flexural fatigue) that initiates at the bottom of the HMA layer and propagates upward needs to be considered. In a composite structure, as shown in Figure 2b, the critical strain location for flexural fatigue (tensile strain) is shifted to a tensile stress location at the bottom of the rigid layer.

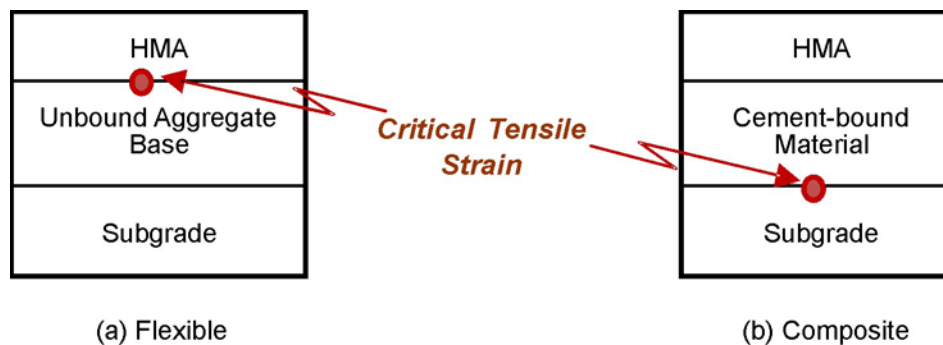


Figure 2. Shift in Critical Strain Location from a Typical Flexible Pavement (Left) to a Composite Pavement (Right)

Past Performance (Literature Review)

Composite pavements have been implemented worldwide in the last few decades. In Europe, composite pavements have been used extensively; countries such as Germany, France, and Spain are known for their wide use of long-life semi-rigid structures in their main road networks, which account for 30% to 50% of their highway systems (Thogersen et al., 2004).

The U.K. highway agencies have used two designs for their flexible composite pavements for the past 20 years. The first design has a service life of up to 20,000,000 equivalent single-axle loads (ESALs) over 20 years and has a structure comprised of a lean concrete base with a maximum thickness of 250 mm (10 in) surfaced with up to 150 mm (6 in) of HMA. The second design is for service a life of more than 20,000,000 ESALs and consists of a 200-mm thick HMA on top of a lean concrete base (Parry et al., 1997). The U.K. had, as of 1999, 649 km of composite pavements in their main road network, which had been constructed between 1959 and 1987 and had carried between 8 and 97 million single-axle (MSA) loads. A composite pavement performance study published by Parry et al. (1999) concluded that there was considerable variability in the performance of these composite structures. In particular, the required thickness of the asphalt overlays during maintenance was highly variable. The new U.K. Pavement Design Guide includes a new section that deals with flexible composite pavement design and that aims to design pavement structures for traffic levels of 100 MSA or more (U.K., 2006).

A study by Merrill et al. (2006) reviewed the experiences of composite pavements in Europe. The authors found that composite pavements from the U.K., the Netherlands, and Hungary were performing satisfactorily in terms of rutting, cracking, and deflections. The expected life of a semi-rigid pavement structure was found to be statistically longer than that of a comparable flexible one. Semi-rigid structures with relatively thin layers (250 mm [10 in] total thickness) performed satisfactorily for a long-life even under heavy traffic. Moreover, field observations confirmed that composite structures tend to have longer lives (i.e., they may be classified as long-life pavements).

There is a very wide use of composite pavements in Spain as documented by Jofre and Fernandez (2004). Composite pavement structures in Spain are called semi-rigid pavements because they do not tend to use a portland cement concrete pavement (PCCP) as the base. Instead they use different types of rigid bases that mainly differ from one another in the cement content and aggregate type. The typical rigid base characterization presented by Jofre and Fernandez is summarized in Table 1.

In the United States, composite pavements usually have been the result of PCCP rehabilitation, consisting of HMA overlays on top of deteriorated rigid pavements and thus creating a composite structure. This type of rehabilitation action has been used to restore the functional performance of an existing pavement and/or to increase the structural capacity in order to handle additional and heavier traffic. The performance of composite pavements may vary due to different factors, such as design of the rigid base, selection of an adequate HMA type, constructability, and maintainability. A study of composite pavements presented by Hein et al. (2002) concluded that:

- The use of an open-graded HMA interlayer does not mitigate reflection cracking
- There is an early (3 to 5 years) deterioration due to reflective cracking on the HMA from the underlying rigid layer's discontinuities
- The pavement condition ratings based only on the HMA surface do not accurately reflect the condition of the overall pavement structure and/or concrete base, e.g., faulting and spalling may be effectively hidden from view.

Table 1. Typical Properties of Rigid Bases Used in Spain

Rigid Base	7-Day Compressive Strength	E-modulus	Description
Soil-Cement	> 2.5 MPa ^a (> 360 psi)	6,000 to 10,000 MPa (870 to 1,450 ksi) ^b	Granular material + cement content 3 to 7%
Gravel-Cement	> 4.5 MPa (> 650 psi)	20,000 MPa (2,900 ksi)	No fine material and a dense gradation
Gravel-Cement Type II	> 8 MPa (> 1,160 psi)	25,000 MPa (3,600 ksi)	Similar to gravel-cement, except for a higher cement content 5 to 7%
Lean-Mix Compacted Concrete	> 12 MPa (> 1,740 psi)	25,000 MPa (3,600 ksi)	Cement content 5 to 10%. Similar to the RCC in the U.S.
Compacted Concrete	> 18 MPa (> 2,600 psi)	33,000 MPa (4,790 ksi)	Cement content 10 to 14%

^a1 MPa = 145.04 psi; ^b1 ksi = 1,000 psi

Composite Pavement Design

This section discusses the various methods currently in use to design composite pavement structures.

AASHTO 1993 Guide

The 1993 AASHTO Guide for Design of Pavement Structures can be used to design two different composite pavements: (1) a new flexible pavement with a cement-treated (or soil-cement) base and (2) a rehabilitated PCC pavement using the section in the guide for the design of AC overlays of PCC (both jointed plain concrete pavement [JPCP] and continuously reinforced concrete pavement [CRCP]).

In the first alternative, it is critical to select a proper layer coefficient, a_2 , for the stabilized base to use the flexible SN design equation:

$$SN = a_1 D_1 + m_2 a_2 D_2 + m_3 a_3 D_3 \quad (1)$$

where

SN = structural number

a_1, a_2, a_3 = layer coefficients

m_2, m_3 = drainage coefficients

D_1, D_2, D_3 = thickness of each layer in inches (layer 1 = HMA, layer 2 = base, layer 3 = subbase)

A study performed by Richardson (1996) provides a general equation that could be used to determine the modulus, E_c , of various cemented materials (e.g., soil cement, cement-treated bases, cement-stabilized soils) and with that, compute the layer coefficient a_2 . Once the cemented material coefficient and all other needed parameters are obtained, the composite structure can be designed.

$$E_c = -34.367 + 2006.8(q_u)^{0.7784} \quad (2)$$

$$a_2 = -2.7170 + 0.49711 \times \text{Log}(E_c) \quad (3)$$

where

E_c = chord modulus (MPa)

q_u = unconfined compressive strength (MPa).

The second alternative for using the AASHTO 1993 guide is based on the procedure for designing the rehabilitation of PCC pavements with an AC overlay. In this case, the first step is to design a conventional PCC pavement, in other words, compute the thickness to satisfy the future traffic demand, D_f . Once the slab thickness has been obtained, it could be assumed that placing an AC layer with a thickness of approximately 50 mm (2 in) would allow for the decrease of 25 mm (1 in) of PCC layer. This is because the guide's "AC Overlay of PCC Pavement" procedure indicates that the required thickness, D_{OL} , of an AC overlay of PCC is calculated using the following equation:

$$D_{OL} = A(D_f - D_{eff}) \quad (4)$$

Where

A = factor to convert PCC thickness deficiency to AC overlay thickness

D_f = slab thickness to carry future traffic (in)

D_{eff} = effective thickness of existing slab (in).

Therefore, two assumptions are made. First, in a new composite pavement design, D_{eff} is equal to D_f because it is appropriate to assume that a newly constructed PCCP would not have any distress, thus none of the adjustment factors shown in Equation 5 would be applicable.

$$D_{eff} = F_{jc} \times F_{dur} \times F_{fat} \times D \quad (5)$$

Where

D = original slab thickness (this would be equal to the thickness of the rigid base)

F_{jc} , F_{dur} , F_{fat} = adjustment factors for joints and cracks, durability, and fatigue = 1.

The second assumption involves the A factor from Equation 4. According to the guide, the A factor is computed using the following equation:

$$A = 2.2233 + 0.0099(D_f - D_{\text{eff}})^2 - 0.1534(D_f - D_{\text{eff}}) \quad (6)$$

Assuming that $D_f = D_{\text{eff}}$, a conservative value of $A = 2.2233$ would be obtained. Lower A values, and consequently HMA thicknesses, may be obtained if using the actual D_f and D_{eff} values. For example, a 150 mm (6 in) HMA layer is required to substitute an HMA thickness of 87.5 mm (3.5 in) of PCCP in the example considered in this report. Once the overlay thickness is computed, it is typically rounded to the nearest 0.5 in.

U.S. Army and Air Force Design

The U.S. Department of Defense has developed a Pavement Design Manual for Roads, Streets, and Open Storage Areas that includes a section for flexible pavements with stabilized bases (UFC, 2004). Such structures would constitute a semi-rigid pavement when a CTB is used underneath the HMA layer.

The pavement design software PCASE developed by the U.S. Army and Air Force for airport pavements uses the procedure described in their guide that is based on an asphalt strain criteria. Equation 7a is used to determine the limiting tensile strain at the bottom of the asphalt layer (UFC, 2004):

$$\text{Allowable Strain} = \varepsilon_{\text{AC}} = 10^{-A} \quad (7a)$$

$$A = \frac{N + 2.665 \times \text{Log}\left(\frac{E}{14.22}\right) + 0.392}{5} \quad (7b)$$

Where

$N = \log(\text{coverage})$

$E = \text{elastic modulus of asphalt concrete (psi)}$.

Once the allowable strain is calculated, the allowable coverage of load repetitions is approximated using the following equations:

$$\text{Allowable Coverage} = 10^X \quad (7c)$$

$$X = 5 \times \text{Log}(\varepsilon_{\text{AC}}) + 2.665 \times \text{Log}\left(\frac{E}{14.22}\right) + 0.392 \quad (7d)$$

where

$\varepsilon_{\text{AC}} = \text{allowable (tensile) strain}$.

Illinois Department of Transportation (IDOT) Design

The Illinois Department of Transportation (IDOT) includes a design procedure and guidelines for new composite pavement design in its Pavement Design Guide published in 2002.

This agency defines a composite pavement as a structure consisting of an HMA surface course overlaying a PCC slab of relatively high bending resistance that acts as the principal load-distributing component of the pavement system (IDOT, 2002).

This comprehensive design methodology includes sections such as potential use of composite pavements, minimum material requirements, design period, structural design, traffic factors, subgrade requirements, performance graded (PG) binder selection, design reliability, minimum design thickness, pre-adjusted slab thickness, slab thickness adjustments, and typical sections.

The equation provided to compute the thickness of the new HMA overlay, D_O , is the following:

$$D_O = \frac{SN_C - 0.33 \times D_B}{0.40} \quad (8)$$

Where

- D_O = thickness of HMA layer for new composite pavement (in)
- SN_C = composite pavement structural number (obtained from a nomograph in their guide)
- D_B = thickness of new PCC base course (in).

After the composite pavement design has been completed, it should be compared to the minimum thickness and material requirements that are provided in the guide. Table 2 shows these requirements.

Table 2. Minimum Thicknesses and Material Requirements for Composite Pavements

Structural Number (SN_C)		Minimum Thickness (in)	Minimum Material
From	To	Surface & Binder	Surface & Binder
< 2.50		2	SUPERPAVE with Low ESALs
2.51	-- 2.99	3	SUPERPAVE with Low ESALs
3.00	-- 3.49	3	SUPERPAVE (4% voids)
> 3.50		4	SUPERPAVE (4% voids)

U.K. Pavement Design Guide

The Highways Agency in the U.K. has extensive experience with composite pavement specifications, design, construction, and testing. Composite pavements are commonly referred to as “flexible composite pavements.” The design methodology and procedure used in the U.K. Pavement Design Guide is based on the TRL Report 615 (Nunn, 2004).

The U.K. design method uses a nomograph to obtain two parameters: (1) the thickness of the hydraulically bound material (HBM) base and (2) the flexible surfacing thickness on top of a HBM base. First, the foundation stiffness (modulus of resilience) is categorized based on the following ranges:

- Class 1 ≥ 50 MPa (7,252 psi)

- Class 2 \geq 100 MPa (14,503 psi)
- Class 3 \geq 200 MPa (29,007 psi)
- Class 4 \geq 400 MPa (58,015 psi)

Second, the hydraulically bound base thickness is obtained as a function of the cement-bound material (CBM) category described in Table 3.

The properties of the base materials are shown in Table 4. Once the thickness of the base is obtained, the thickness of the asphalt layer can be obtained from Equation 9.

$$H_{\text{asphalt}} = -16.05 \times (\text{Log}(N))^2 + 101 \times \text{Log}(N) + 45.08 \quad (9)$$

where

H_{asphalt} = asphalt thickness (mm) (for 50 MSA < N < 80 MSA)

N = cumulative traffic (MSA = million single axles = 1,000,000 ESALs).

Table 3. Design Thicknesses for CBM Base for More than 80,000,000 ESALs

CBM Base	Foundation Class			
	Class 1 50 MPa (7,250 psi)	Class 2 100 MPa (14,500 psi)	Class 3 200 MPa (29,000 psi)	Class 4 400 MPa (58,000 psi)
CBM3G	275 mm (10.8 in)	250 mm (9.8 in)	225 mm (8.9 in)	200 mm (7.9 in)
CBM4G	220 mm (8.7 in)	200 mm (7.9 in)	180 mm (7.0 in)	150 mm (5.9 in)
CBM5G	200 mm (7.9 in)	180 mm (7.0 in)	160 mm (6.3 in)	150 mm (5.9 in)
CBM3R	220 mm (8.7 in)	200 mm (7.9 in)	180 mm (7.0 in)	150 mm (5.9 in)
CBM4R	200 mm (7.9 in)	180 mm (7.0 in)	160 mm (6.3 in)	150 mm (5.9 in)
CBM5R	165 mm (6.5 in)	150 mm (5.9 in)	150 mm (5.9 in)	150 mm (5.9 in)

Table 4. Properties of CBM

CBM	Minimum 7-day Compressive Strength, MPa (psi)
CBM1	4.5 (653)
CBM2	7.0 (1,015)
CBM1A	10.0 (1,450)
CBM2A	10.0 (1,450)
CBM3R/G	10.0 (1,450)
CBM4R/G	15.0 (2,175)
CBM5R/G	20.0 (2,900)

The Danish Road Institute (Report 138)

In 2004, the Danish Road Institute published a mechanistic design guide for semi-rigid pavements (Thogersen et al., 2004). This mechanistic guide was developed as a result of a survey that showed the superior performance of pavements with CTB, especially on heavily trafficked pavement sections. In order to understand the behavior of such pavements and establish a mechanistic design, a full-scale test on six semi-rigid pavements (three different types, each with two replications) was carried out. A generalized incremental-recursive model based on tensile strain at the bottom of the CTB layer was chosen as the desired approach to verify the deterioration model (Thogersen et al., 2004). The results were then compared to existing semi-rigid pavements that had been in service for more than 20 years. The comparison of these results showed that the deterioration model was accurate.

The study focused on the failure of the semi-rigid structure in terms of fatigue of the rigid layer. The determining factor in the fatigue damage was the longitudinal (tensile) strain at the bottom of the CTB layer. The investigation concluded that for their semi-rigid pavement structure, at 75 percent confidence, the following deterministic design criterion should be used to prevent fatigue failure of the structure:

$$\varepsilon_{\text{PERMISSIBLE}} = 99\mu_{\text{str}} \times \left(\frac{N}{10^6} \right)^{-0.12} \quad (10)$$

where

$\varepsilon_{\text{PERMISSIBLE}}$ = maximum strain at bottom of CTB layer

μ_{str} = micro-strain (10^{-6} strain)

N = number of load repetitions (passes) to failure.

Once the mechanistic behavior of the semi-rigid structure was modeled, the criterion constants were utilized to provide designs for various traffic volumes (Thogersen et al., 2004). In the design table (Table 5), the load is represented as a dual-wheel load with 20 % dynamic load additions as used in the new Danish design standards.

Table 5. Semi-rigid Pavement Design for the Danish Road Institute (Thogersen et al., 2004)

Layer		Number of Equivalent 10-ton Axles (million)							
		0.2	0.5	1	2	5	10	20	50
Asphalt surface and binder	E = 2,500 MPa (362.6 ksi)	60 (2.5)		80 (3.5)					
	Thickness in mm (in)								
CTB with $E_{\text{initial}} = 12,000$ MPa	Allowable initial strain, μstr	65	57	51					
	Required thickness, mm (in)	215 (8.5)	235 (9.3)	245 (9.6)					
CTB with $E_{\text{initial}} = 16,000$ MPa	Allowable initial strain, μstr			75	69	62	57	52	47
	Required thickness, mm (in)			150 (5.9)	165 (6.5)	180 (7.1)	190 (7.5)	205 (8.0)	225 (8.9)
Gravel base	E = 300 MPa (43.5 ksi)	Thickness 150 mm (5.9 in)							
Subbase	E = 100 MPa (14.5 ksi)	Thickness minimum 200 mm (7.9 in)							
Subgrade	E = 40 MPa (5.8 ksi)	-							

Composite Pavement Performance

A composite pavement structure, throughout its service life, may develop different types of distresses. The distresses that affect composite pavements, according to Von Quintus et al. (1979), are very similar to those of flexible pavements because of the exposure that the asphalt concrete layer has in the composite structure. The distresses may be grouped into three major categories: fracture (cracking), distortion, and disintegration. All of the mentioned distresses could potentially affect the performance and structural capacity of composite pavements. However, the majority could be mitigated with a high-quality HMA mix, adequate overall structural design, and appropriate constructive procedures.

Several research studies (Von Quintus, 1979; Smith et al., 1984; NCHRP, 2004) have agreed that reflective cracking (also known as reflection cracking) is a major distress type in composite pavements. Reflective cracks are cracks that occur in the asphalt surface course of the composite pavement and that coincide with cracks with appreciable width or joints in the underlying layer. They are caused by the relative horizontal and vertical movements of these cracks or joints caused by temperature cycles and/or traffic loading.

Reflective cracks are undesirable in a composite pavement structure as they tend to undergo a progressive width increase, permitting the leakage of surface water to the layer beneath. This may cause raveling and disintegration of the asphalt surfacing adjacent to the cracks (Breemen, 1963). When a crack has a considerable width, it acts as a joint and high stress intensity is generated at this location. The contraction and expansion of the rigid layer tends to open and close this "joint" causing a significant change in width; as a result, the tensile stresses induced at the bottom of the HMA surface layer exceed the strength of the asphalt overlay and a reflective crack is initiated.

When a chemically stabilized material (CSM) is used as the rigid base (e.g., CTB), drying shrinkage during the curing period is a major cause for the cracking of the base. The reasons that contribute to shrinkage cracking occurrence, which then lead to reflective cracks, include material characteristics, construction procedures, traffic loading, and restraint imposed on the base by the subgrade (Adaska and Luhr, 2004).

The proposed Mechanistic-Empirical Pavement Design Guide (MEPDG) mentions the following points regarding the use of CSM base layers (NCHRP, 2004): (1) if there is an HMA surface course (composite pavement scenario), any fatigue cracking in the CSM layer *will* result in a fraction of the cracking reflected through the HMA layer; and (2) if a crack relief layer (e.g., unbound granular layer) is placed between the HMA and CSM layer, it is possible to minimize or potentially eliminate reflective cracking through the HMA layer.

To mitigate and control reflective cracks, various methods and techniques could be used. These include the use of crack relief layers, pre-cracking (microcracking) of the cemented base, and use of geotextiles (paving fabrics) (Adaska and Luhr, 2004).

RESULTS

This section discusses the results of the state-of-the-practice survey and the technical and economic analyses conducted. The technical analysis included a comparison of the different design methodologies for composite pavement systems and modeling of typical distresses affecting composite pavement systems. This modeling helped understand how the distresses affected different composite structures as compared to traditional flexible pavements and among themselves. The economic analysis consisted of a LCCA to investigate the cost implications at both the initial construction stage and throughout the pavement service life. Four pavement structures were considered: traditional flexible, traditional rigid, composite with CTB, and composite with CRCP base.

State-of-the-Practice Survey

A web-based survey was distributed to all state pavement engineers to investigate the extent of the use of composite pavements in the U.S. The survey questions are presented in Appendix A and the results are shown in Appendix B. Responses, received from 34 state DOTs, suggested that several agencies have composite pavements that are the result of an HMA overlay of an in-service, and likely distressed, rigid pavement. In addition, three DOTs reported that they had some degree of experience in designing and constructing new composite pavements (i.e., composite pavements that did not result from an HMA overlay of a distressed concrete pavement).

The South Carolina Department of Transportation (SCDOT) uses the AASHTO 1993 method to design composite pavements. Approximately 2% of their road network consists of newly constructed composite pavements. These pavements typically consist of a dense-graded HMA placed on a CTB. SCDOT uses a structural coefficient of 0.34/in for the cement-stabilized aggregate base. In addition, a minimum base thickness of 150 mm (6 in) with a preferred

thickness of 200 mm (8 in) to 250 mm (10 in) is required due to the brittle nature of the material. The typical cement content for the base course is 2% to 5% (by weight) with a 4.14 MPa (600 psi) compressive strength requirement at 14 days.

The Texas Department of Transportation (TxDOT) uses their own FPS-19W software to design new composite pavements and their network includes an estimated 4% of newly constructed composite pavements. The composite structure that is used in Texas is HMA on cement stabilized base (CSB). TxDOT recommends that the modulus of the base, during the design input process, should not exceed 1725 MPa (250 ksi) to not “underdesign” the total structural thickness. Their recommendations for compressive strength are in the range of 2.07 MPa (300 psi) to 2.76 MPa (400 psi) in hopes to avoid thermal/shrinkage cracking. The typical cement content is 3% to 4% (by weight), resulting in a 7-day compressive strength of 2.41 MPa (350 psi) for the rigid base layer.

The Tennessee Department of Transportation (TnDOT) uses the AASHTO method to design their new composite pavements, which comprise approximately 2% of their network. The agency uses composite pavements consisting of HMA over CTB, and HMA over lime fly-ash treated bases. The designs are normally used on interstates, freeways, or multi-lane divided arterial highways.

Technical Analysis

To understand the technical advantages of composite pavements, a technical evaluation was performed. This evaluation involved mechanistic modeling of a typical composite pavement structure that was obtained using the most promising methodologies available for the design of composite systems.

Designed Composite Pavement Structures

To compare the output (primarily thicknesses) and layer recommendations from the different design methodologies, it was important to design composite pavement systems for a fixed set of conditions (inputs). Therefore, the various design procedures were followed to design composite pavement structures for the same input parameters (e.g., traffic, design life). Table 6 shows the basic design inputs and Table 7 the typical values used for the material properties of each layer used for the structures. (NCHRP, 2004; Huang, 2004).

Table 6. Parameters Used for the Design of Composite Structures

Parameter	Value
Design life	40 years
Traffic	50,000,000 ESALs ^a 58,230 ADT, ^b 12% trucks
Reliability	95% (AASHTO design) 75% (Danish design)
PSI _o ^c	4.5
PSI _f	3.0
^a ESAL = number of equivalent single axle loads, in accordance with the 1993 AASHTO Pavement Design Guide ^b ADT = annual daily traffic ^c PSI = present serviceability index	

Table 7. Typical Material Properties for the Composite Pavement Layers

Layer No.	Material	Elastic Modulus MPa (psi)	Poisson's Ratio	Modulus of Rupture MPa (psi)
1	HMA	3,448 (500,000) [†]	0.35	N/A
2	PCC <i>or</i>	24,138 (4,000,000)	0.15	4.48 (650)
	RCC <i>or</i>	13,793 (3,500,000)	0.15	4.14 (600)
	Lean mix concrete <i>or</i>	6,896 (2,000,000)	0.15	3.10 (450)
	CTB <i>or</i>	3,448 (1,000,000)	0.20	1.38 (200)
	Soil Cement	3,448 (500,000)	0.20	0.69 (100)
3	Base <i>and/or</i>	207 (30,000)	0.35	N/A
	Subbase	138 (20,000)	0.35	N/A
4	Subgrade (compacted, CBR=5%)	51.7 (7,500) [*]	0.40	N/A

[†] Typical value at an average service temperature.

For the two AASHTO alternatives, a simple spreadsheet was created to compute all the values obtained from the AASHTO 1993 guide. The IDOT alternative was computed using the tables, formulas, and nomographs published in their 2002 Pavement Design Guide (IDOT, 2002). The U.S. Air Force and Army alternative was designed using the PCASE pavement design software available from their website (PCASE, 2007). The Danish design was based on the Danish Road Institute mechanistic design table with a 75% reliability (Thogersen et al., 2004). The U.K. design thicknesses were obtained using Equation 9. Figure 3 compares the cross sections of all the composite structures designed using the various procedures.

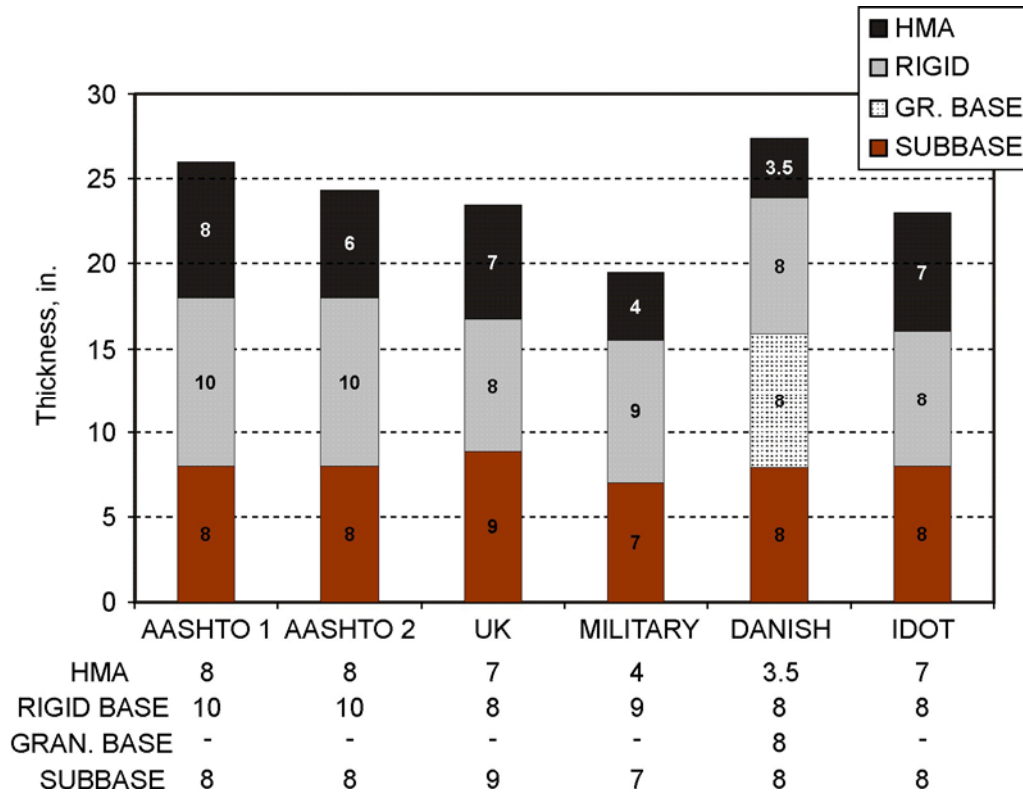


Figure 3. Comparison of All Designed Composite Pavement Structures

The composite structures shown in Figure 3 ranged from a total thickness of 20 to 28 in. These structures may be grouped into three design groups according to similar thicknesses in the HMA and rigid base layer:

- Group 1, composed by the two AASHTO alternatives that resulted in an 8-in HMA surface course and a 10-in rigid base. In the AASHTO 1 alternative, flexible pavement procedure with a CTB, the structural coefficient of the HMA, $a_1 = 0.47$, was greater than the CTB, $a_2 = 0.27$. In the AASHTO 2 alternative, rigid pavement procedure with HMA rehabilitation, the structural package was similar to the AASHTO 1 alternative, with the exception of a thinner HMA layer.
- Group 2, composed the U.K. and IDOT designs that resulted in very similar designs consisting of a HMA of 175 mm (7 in) and a rigid base of 200 mm (8 in). The rigid bases in these two designs were a lean-mix concrete and a PCC for the U.K. and IDOT procedures, respectively. The layers' designed thicknesses obtained by following the design procedure of these transportation agencies were chosen as the typical composite pavement to be analyzed through the mechanistic modeling. The main reason why this design was selected is because of the experience in the U.K., which, according to the literature, is one of the countries that has the most experience investigating, designing, and constructing composite pavement systems in the last two decades.
- Group 3, composed by the military and Danish designs, which had the lowest thicknesses for the HMA surface layer. Although the thickness of these layers are lower than for the other cases, the Washington State Department of Transportation specifies, based on experience, that a 100 mm (4-in) HMA thickness is thought to be thick enough to retard reflective cracking (WSDOT, 2007). The Danish alternative is the only one that proposes the use of a granular base layer underneath the rigid base and above the subbase layer. However, the presence of this granular base layer could be due to the lower modulus of the subgrade (40 MPa [5,800 psi]) used as fixed values in their design table (Table 5). In addition, this alternative had the lowest HMA surface thickness (87.5 mm [3.5 in]).

Mechanistic Analysis

In order to understand and model pavement behavior and responses (e.g., stress, strain, and deflections), a mechanistic-based analysis was performed. The MICH-PAVE software, available as a freeware, was used to model the mechanistic responses of the composite structures. MICH-PAVE is a non-linear finite element software for the analysis of flexible and rigid pavements. The program calculates displacements, stresses, and strains within the pavement structure due to a single circular wheel load (Harichandran and Baladi, 2000). A user-defined mesh can be visualized using the software, and the nodes that compose the mesh are used to compute pavement responses at specific locations at both vertical and radial distances from the applied load. The software outputs were also compared with those of layered linear elastic software prior to using them in this study; the obtained results were very similar.

Mechanistic analyses were performed on various composite structures to understand their behavior as various rigid bases were used. The material properties (i.e., elastic modulus, Poisson's ratio) used are given in Table 7. Because of the extensive experience with this type of pavements in the U.K., the composite structure analyzed was based on the U.K. design and included the following input parameters:

- Surface course: HMA layer: 175 mm (7 in) thickness
- Base course: (granular, soil cement, CTB, lean mix, RCC, or PCC): 200 mm (8 in)
- Subbase: granular subbase: 150 mm (6 in) thickness
- Subgrade: compacted subgrade; at least 300 mm (12 in)
- Load: one 40-KN (9,000-lb) load with a tire pressure of 0.83 MPa (120 psi) (for deflections, two 20-KN [4,500-lb] loads with the same tire pressure were used).

Distress Transfer Functions

Fatigue Cracking. In order to model the fatigue cracking distress two approaches were taken: (1) model the number of load repetitions to fatigue failure of the HMA layer, and (2) model the number of load repetitions to fatigue failure of the rigid base layer.

The modeling of fatigue failure of the HMA layer was based on the model presented by the proposed MEPDG (NCHRP 1-37A), which is based on the Asphalt Institute fatigue model.

$$N_f = 0.00432 \times k'_1 \times C \left(\frac{1}{\varepsilon_t} \right)^{3.291} \left(\frac{1}{E} \right)^{0.854} \quad (11)$$

$$C = 10^M \quad (12)$$

$$M = 4.84 \left(\frac{V_b}{V_a + V_b} - 0.69 \right) \quad (13)$$

where

N_f = number of load repetitions to fatigue cracking

k'_1 = parameter used for either bottom-up or top-down criteria

ε_t = tensile strain at critical location

E = stiffness of material (HMA)

V_b = effective binder content (%)

V_a = air voids (%)

For bottom-up cracking, the k'_1 parameter is:

$$k'_1 = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{(11.02 - 3.49 \times h_{ac})}}} \quad (14)$$

where

h_{ac} = total thickness of asphalt layer (in).

In the rigid layer fatigue case, the modeling was based on two criteria: (1) the MEPDG CSM fatigue failure transfer function for soil cement, CTB, and lean mix (Equation 15) and (2) the PCA concrete fatigue failure transfer function for RCC and PCC (Equations 16 through 19).

$$\log(N_f) = \frac{\left(0.972\beta_{c1} - \left(\frac{\sigma_t}{MR}\right)\right)}{0.0825\beta_{c2}} \quad (15)$$

where

N_f = number of repetitions to fatigue cracking of the CSM layer

σ_t = maximum traffic-induced tensile stress at the bottom of the CSM layer (psi)

MR = 28-day modulus of rupture (flexural strength) (psi)

β_{c1} , β_{c2} = field calibration factors; the default factor of 1 was used for this study.

$$SR \geq 0.55: \quad \text{Log}(N_f) = 11.737 - 12.077 \times SR \quad (16)$$

$$0.45 < SR < 0.55: \quad N_f = \left(\frac{4.2577}{SR - 0.4325}\right)^{3.268} \quad (17)$$

$$SR \leq 0.45: \quad N_f = \text{unlimited} \quad (18)$$

where

SR = ratio of equivalent stress to PCC flexural strength (as defined in Eq. 19)

N_f = allowable number of repetitions to fatigue cracking.

$$SR = \frac{\sigma_{eq}}{MR} \quad (19)$$

where

σ_{eq} = equivalent stress = flexural stress in slab

MR = modulus of rupture of concrete = PCC flexural strength.

Permanent Deformation (Rutting) Modeling. The modeling of rutting in the HMA layer uses the relationship from the MEPDG (NCHRP, 2004), Equation 20, to obtain the accumulated plastic strain. This strain results from the sum of various plastic strain deformations inside the bituminous layer, which can be used to determine the rut depth after a specific number of load repetitions. To compute the rut depth, the HMA layer is divided into sub-layers according to the criterion described in the MEDPG, and plastic strains are computed at various points located at different depths from the surface.

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \times 10^{-3.4488} \times T^{1.5606} \times N^{0.479244} \quad (20)$$

where

- ε_p = accumulated plastic strain at N repetitions of load (in/in)
- ε_r = resilient strain of the asphalt material as a function of mix properties, temperature, and time rate of loading (in/in)
- N = number of load repetitions
- T = temperature (°F)
- k_1 = parameter computed from Equation (21).

$$k_1 = (C_1 + C_2 \times \text{depth}) \times 0.328196^{\text{depth}} \quad (21)$$

$$C_1 = -0.1039 \times h_{ac}^2 + 2.4868 \times h_{ac} - 17.342 \quad (22)$$

$$C_2 = 0.0172 \times h_{ac}^2 - 1.7331 \times h_{ac} + 27.428 \quad (23)$$

where

- k_1 = confining pressure correction factor
- h_{ac} = total asphalt layers thickness (in)
- depth = depth to computational point (in).

Reflective Cracking. The reflective cracking modeling was based on a mechanistic-empirical overlay design method for reflective cracking proposed by Sousa et al. (2002). The study focused on the modeling of reflective cracking above cracks in the underlying pavement surface. Both dense-graded HMA and gap-graded asphalt rubber (wet process) mixes were studied in the laboratory and field to derive mechanistic relationships and statistically based equations. The measured versus predicted crack activity, both before and after the overlay was placed, was investigated. The Von Mises strain, necessary for the modeling, was developed as the following:

$$\varepsilon_{VM} (1 \times 10^{-6}) = a \times (\text{Overlay Thickness (m)})^b \quad (24)$$

where

ϵ_{VM} = Von Mises strain

a, b = coefficients obtained experimentally.

The model was calibrated using iterative processes. Three adjustment factors were developed: aging adjustment factor (AAF), temperature adjustment factor (TAF), and a field adjustment factor (FAF). All of these factors affected the value of ϵ_{VM} , which was used to determine the number of ESALs that can be sustained by the HMA overlay before the onset of reflective cracking. The final model was the following:

$$\text{Asphalt rubber mix: } \text{ESALs} = 4.1245 \times 10^{19} \times \left[\epsilon_{VM} (1 \times 10^{-6}) \right]^{-4.9761} \quad (25)$$

$$\text{Dense-graded mix: } \text{ESALs} = 4.1245 \times 10^{20} \times \left[\epsilon_{VM} (1 \times 10^{-6}) \right]^{-5.93} \quad (26)$$

The number of ESALs obtained from Equations (25) and (26), need to be multiplied by the FAF to obtain the final design ESALs required for the overlay to reach a specific percentage of reflective cracking.

Deflections

Composite pavements have been known to provide greater structural support than traditional flexible pavements, while sharing similar noise, friction, and smoothness properties. High structural support of a pavement structure has been traditionally associated with low deflections at the surface (i.e., deflection measurements are known to be reduced when the bearing capacity of the road is high). In addition, a reduction of deflection under an applied load reduces the traffic-induced stresses and strains within the layers of the structure (Nunn et al., 1997). Therefore, a structure that provides lower deflection measurements would tend to reduce the layers' state of stress and strain, causing the pavement structure to be less affected (damaged) by the loading conditions. The deflection analysis performed is shown in Figure 4.

The figure shows that the modeled deflections at the pavement surface are greatly reduced as the stiffness of the base increases. In this case, the stiffness or elastic modulus (E) of the base increased from soil cement (E = 3,448 MPa [500,000 psi]) to PCC (E = 27,586 MPa [4,000,000 psi]). The maximum deflection predicted when the granular base was used was 0.49 mm (19.2 mils).

Table 8 shows the percent reduction of deflections, when comparing rigid bases to the granular one. As the rigidity of the base increases, the deflections of the pavement structure decrease. This reduction in deflection suggests a reduction of stresses and strains in the various pavement layers, especially in the HMA.

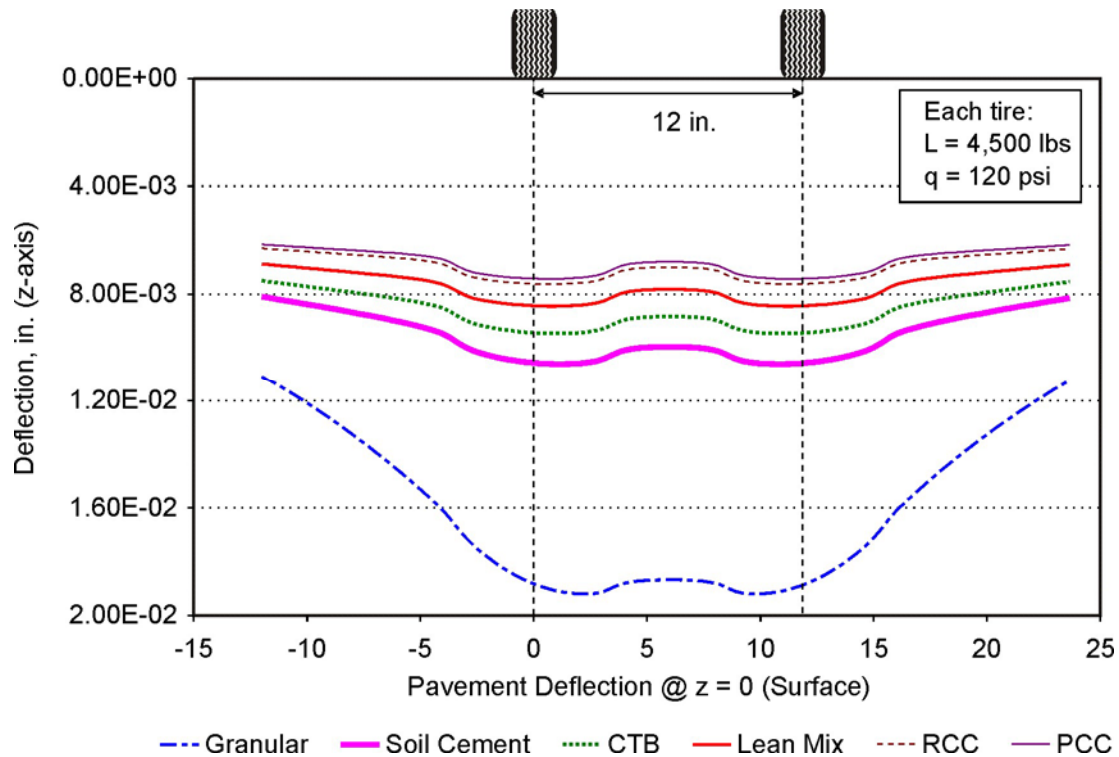


Figure 4. Surface Pavement Deflections of Various Structures

Table 8. Maximum Deflection of Pavement Surface with Different Base Layers

Base Layer	Max. Deflection mm (mils)	Percent Reduction %
Granular	0.488 (19.2)	0
Soil cement	0.264 (10.4)	45
CTB	0.240 (9.45)	51
Lean mix	0.214 (8.43)	56
RCC	0.193 (7.61)	60
PCC	0.188 (7.42)	61

Horizontal Stresses and Strains

A pavement structure, when subjected to a load, presents stress and strain responses that are a function of the load magnitude, load location, pressure, and material properties, among other factors. Horizontal stresses have been investigated in the past to understand their effect on failure of HMA and cement-bound materials (e.g., soil cement, CTB, lean mix, RCC, PCC) (Kennedy, 1983; Balbo, 1993). In addition, horizontal strains have also been investigated to predict HMA and cement-bound material fatigue (Kennedy, 1983; Thogersen et al., 2004; Shook et al., 1982).

The results of the horizontal stress analysis are shown in Figure 5. Two observations from the horizontal stresses output of the mechanistic model can be discussed. First, considerably higher compressive and tensile stresses can be observed in the HMA layer of the typical flexible pavement structure (granular base scenario). In the case of rigid bases, the

magnitude of both compressive and tensile stresses is significantly reduced. For a flexible pavement structure, the highest compressive stress is located at the top of the HMA layer, whereas the highest tensile stress is located at the bottom of the HMA layer. For the case of composite pavements, the stresses at the top and bottom of the HMA are compressive.

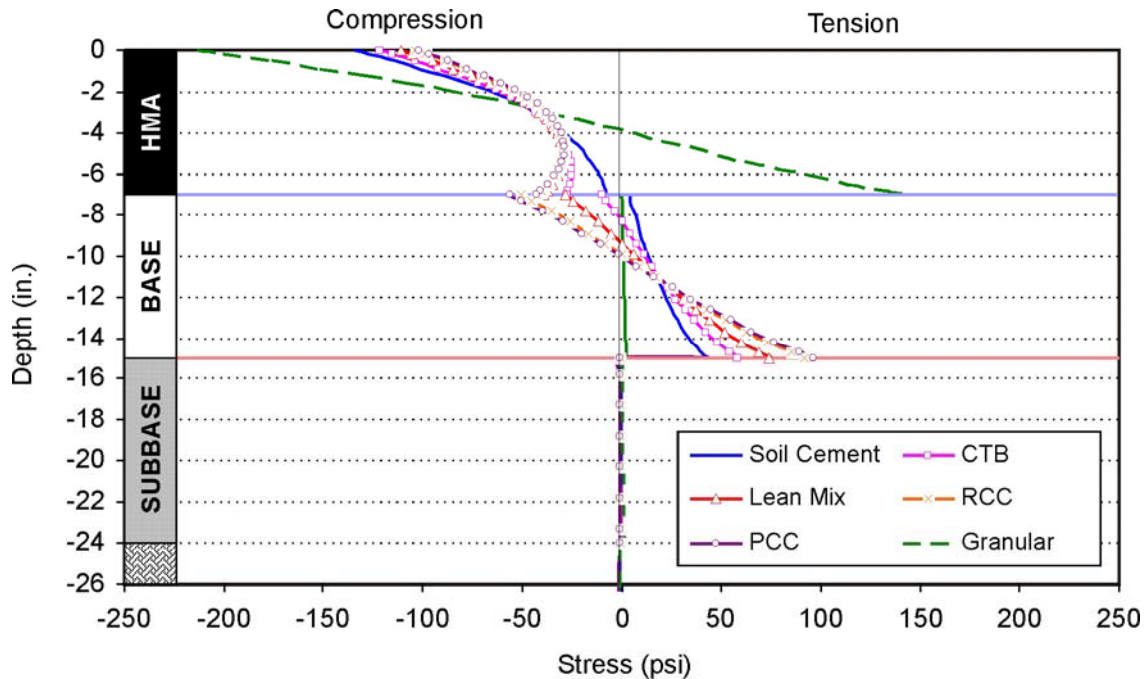


Figure 5. Horizontal Stresses Analysis with Varying Base Stiffness

Second, in the base layer of the typical flexible pavement structure (depths of 175 to 375 mm [7 to 15 in]) the stresses are small because of its low modulus. In the case of composite pavements, higher tensile stresses develop at the bottom of rigid base layer. The magnitude of these stresses increments as the stiffness of the base increases. Consequently, the tensile stress at the bottom of the rigid layer criteria become critical and is the one used to predict fatigue life.

The horizontal strains output obtained from the mechanistic modeling (Figure 6) are consistent with the results from the horizontal stresses. In this case, it can be observed that the tensile strain at the bottom of the HMA, which is the most commonly used point of interest when investigating flexural fatigue damage, is significantly larger in the granular base case than when a rigid base was used. This suggests that the chance of having fatigue failure in the HMA when using a granular base is much higher than that with any composite pavement structure. Furthermore, the tensile strain at the bottom of the HMA only occurs for granular, soil cement, and CTB bases; when lean mix, RCC, and PCC are used as bases, the strains become compressive in nature. Thus the likelihood of fatigue cracking is greatly minimized. This phenomenon was also noted in previous publications (NCHRP, 2004; Donald, 2003).

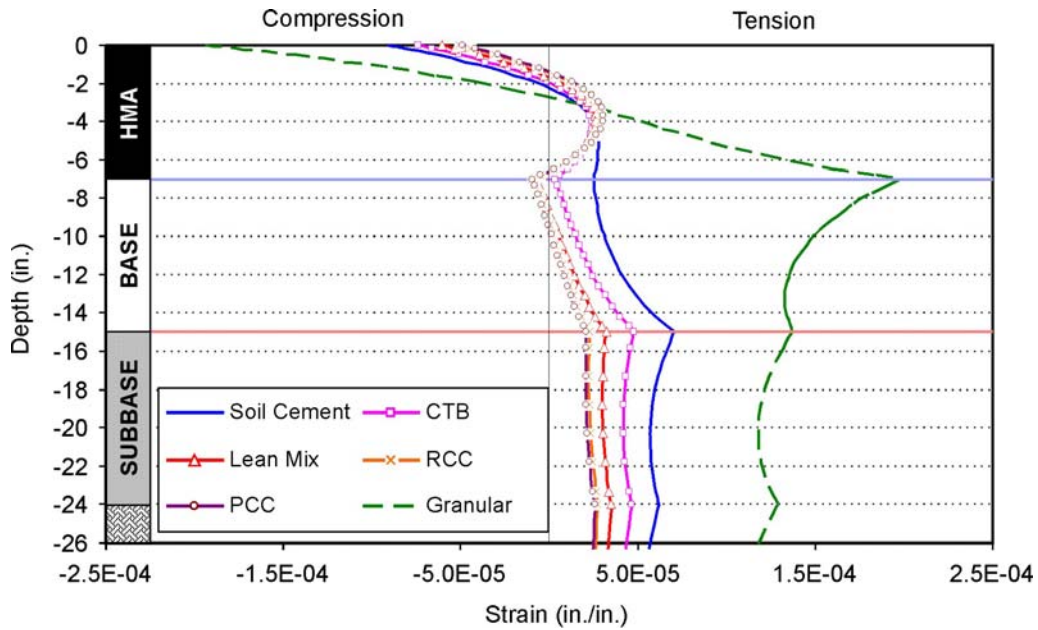


Figure 6. Horizontal Strain Analysis Varying Base Stiffness

Vertical Strains

Vertical strains have been used in the past to determine how much deformation is likely to occur on top of the subgrade and thus help determine rutting due to subgrade permanent deformation (Huang, 2004). In addition, vertical strains are used in the permanent deformation model of the proposed MEPDG. In this model, resilient vertical strain responses are computed to obtain plastic strain accumulations that are then used to compute the rutting within the HMA layer (NCHRP, 2004). The vertical strain analysis performed is shown in Figure 7.

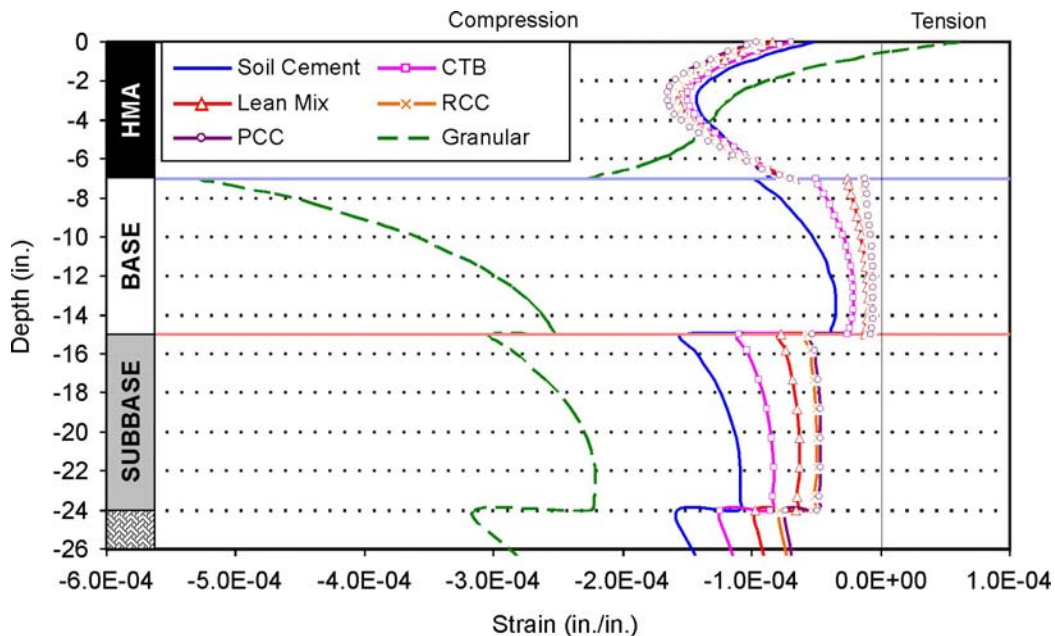


Figure 7. Vertical Strain Analysis Varying Base Stiffness

The mechanistic model output shows an interesting vertical strain distribution especially in the HMA layer (0 to 175 mm [0 to 7 in]). In the pavement system with a granular base, vertical strains at the top region (0 to 12.5 mm [0 to 0.5 in]) are tensile in nature. This is probably due to the boundary conditions imposed by the modeling software. When a lower Poisson's ratio value was used for the HMA (e.g., 0.30), the vertical strains at the top region of the HMA showed compressive responses instead of tensile. The remainder of the strain distribution (granular case) suggests that the rest of the HMA is in compression with the lower region (100 to 175 mm [4 to 7 in]) presenting a greater magnitude of compressive responses. In the case of composite pavements, the highest compressive stresses develop in the middle of the layer. This suggests that higher vertical deformations presented in the HMA are prone to occur in this region (50 to 100 mm [2 to 4 in]).

As the stiffness of the base increases, the compressive strains in the unbound layers (subbase and subgrade) noticeably decrease. The significant reduction of vertical strains at top of the subgrade—at a depth just below 600 mm (24 in)—suggests that rutting due to permanent deformation of the subgrade is greatly minimized or even unlikely to occur.

Mechanistic-Empirical Analysis

Fatigue Cracking Prediction

The transfer functions presented in the preceding sections (Equations 11, 16, and 21) were used to compute the bottom-up fatigue cracking progressions for the HMA and rigid bases based on the critical strain from Figure 6. A summary of the results of the fatigue analysis is shown in Table 9 and illustrated in Figure 8. A line indicating 50,000,000 ESALs is provided as a reference.

Table 9. HMA and Rigid Base Fatigue

Structure	Tensile Strain ($\times 10^{-6}$) bottom of HMA	Tensile Stress (psi) bottom of Rigid layer	Repetitions to HMA Fatigue Failure (ESALs) ^a	Repetitions to Rigid Fatigue Failure (ESALs)
HMA on granular	197	-	12,800,000	-
HMA on soil cement	25	42	44,500,000,000	4,890,000
HMA on CTB	3.4	57	<i>infinite</i>	186,000,000
HMA on lean mix	-	74	<i>infinite</i>	6,260,000,000
HMA on RCC	-	96	<i>infinite</i>	<i>Infinite</i>
HMA on PCC	-	96	<i>infinite</i>	<i>Infinite</i>

^a Note: The V_b and V_a parameters in Equation 13b are assumed to be 7% and 4%, respectively. 1 MPa = 145 psi

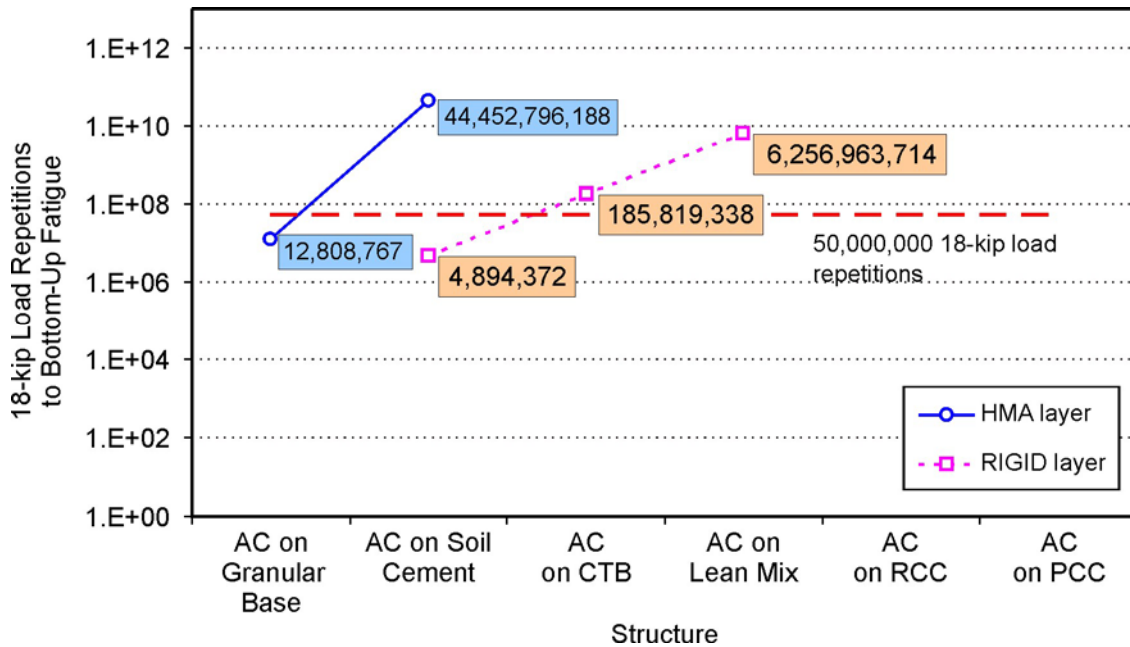


Figure 8. HMA and Rigid Base Repetitions to Fatigue Failure

The number of load repetitions to HMA fatigue failure is much greater in a pavement with a cement-bound base (e.g., soil cement) than in pavement with a granular base. Table 9 shows an infinite number of load repetitions for the HMA on CTB, lean mix, RCC, and PCC base courses; this is because when any of these bases are used, the strain at the bottom of the HMA becomes very small (CTB case) or compressive in nature (lean mix, RCC, and PCC cases) and the flexible layer is highly unlikely to fail due to fatigue cracking.

It can be observed that for composite pavements where the rigid base is a soil cement, CTB, or lean mix, the base is the layer that controls the design in terms of fatigue, as it would fail earlier than the HMA layer. In the case of RCC and PCC fatigue evaluation, the repetitions were determined to be infinite because the stress ratio (SR) term after a load was applied for RCC and PCC were 0.17 and 0.16, respectively. The fatigue behavior of RCC was assumed to be similar to that of conventional PCC as recommended by the American Concrete Institute (ACI) (Delatte, 2004).

Permanent Deformation (Rutting) Prediction

The modeling of rutting in the HMA layer uses the relationship from the proposed MEPDG (NCHRP, 2004), as shown in Equation 20, to obtain the accumulated plastic strain. This strain results from the sum of various plastic strain deformations inside the asphalt layer, which can be used to determine the rut depth after a specific number of load repetitions. To compute the rut depth, the HMA layer is divided into sub-layers according to the criterion described in the MEDPG, and plastic strains are computed at various points located at different depths from the surface.

Figure 9 shows the results obtained for the rutting in the HMA layer in terms of rut depth versus the type of base used. The results suggest that as the stiffness of the base increases, the

rut depth in the HMA layer increases as well. This was an expected outcome because the high rigidity of the base does not allow any significant vertical deformation to occur, thus the HMA layer absorbs all the vertical strains and deforms itself as illustrated (exaggerated for illustration purposes) in Figure 10. The 12.5 mm (0.5 in) rut depth shown in Figure 9 represents the allowable value used by the Asphalt Institute and Huang (2004).

The HMA rutting results show that for 50,000,000 18-kip load repetitions, the typical flexible pavement constructed with a granular base was the only structure that met the 12.5 mm (0.5 in) rut depth criterion. All of the composite pavement structures presented greater (up to 21 mm [0.83in]) degrees of permanent deformation due to the high number of load repetitions. It is noted, however, that the computed rut depth for all the structures (both flexible and composite) assumed no rehabilitation operations at any time during the 50,000,000 load applications. Therefore, if a functional rehabilitation is applied at any time during the service life of the pavement, part of the permanently deformed HMA would be replaced. In addition, the use of premium mixes, such as SMA, may also help reduce the rutting progression. Finally, it is also important to note that the model has not been validated and calibrated to the local conditions.

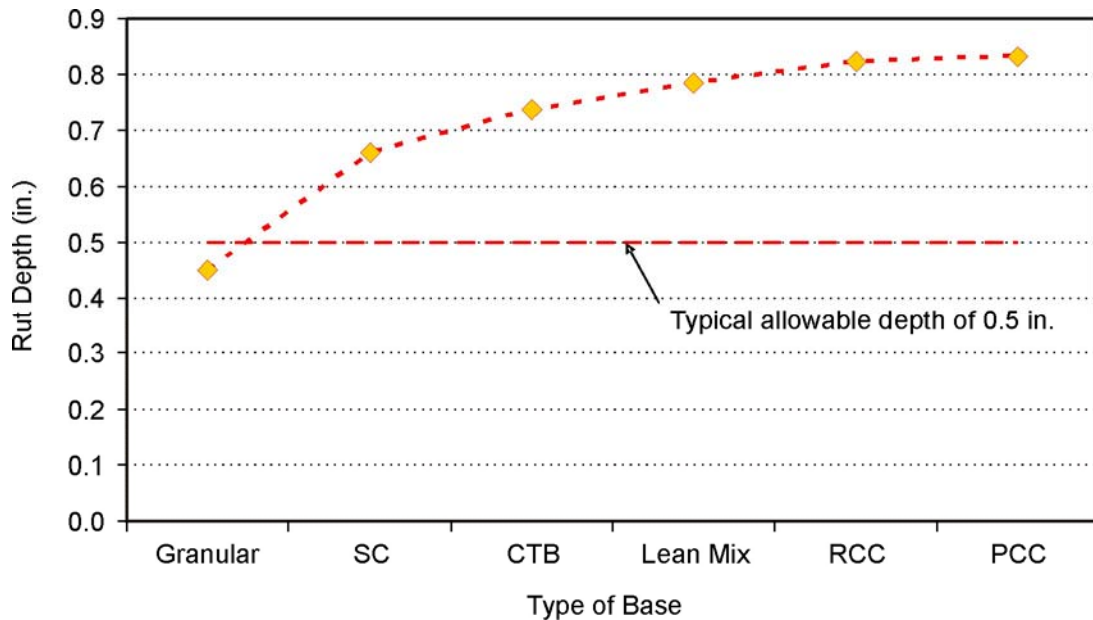


Figure 9. HMA Rut Depth Versus Base Type

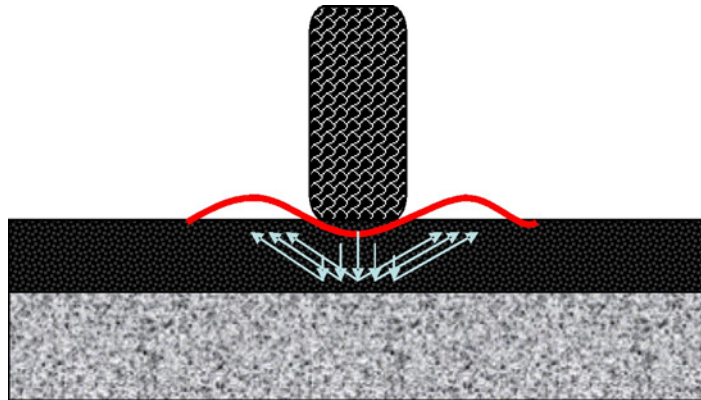


Figure 10. Permanent Deformation (Rutting) in HMA Layer Due to the Rigidity of the Composite Pavement Cementitious Base

Reflective Cracking Prediction

The modeling of reflective cracking was based on the study published by Sousa et al. (2002), which proposed a mechanistic-empirical HMA overlay design that predicts the number of 80.2 kN (18-kip) load repetitions for a predetermined percentage of reflective cracking.

As the thickness of the HMA layer increases, the number of repetitions to achieve a 5% reflective cracking also increases as shown in Figure 11. This mechanistic-empirical model was originally proposed to predict the reflected cracks on an HMA overlay placed on top of a cracked HMA. This model was chosen to investigate reflective cracking in composite pavements because of its practical application to predicting this type of distress on HMA overlays. In addition, very few methodologies or procedures have been published to predict reflective cracking on composite pavement systems (i.e., HMA on PCC or rigid bases), mainly because of the difficulty of modeling the behavior and interface interaction of these two very different materials. However, the findings and proposed procedure by Sousa et al. (2002), which involves the computation of vertical crack activities before and after the overlay is placed, were assumed to be reasonably applicable to a composite pavement system when the typical values of a composite structure are input.

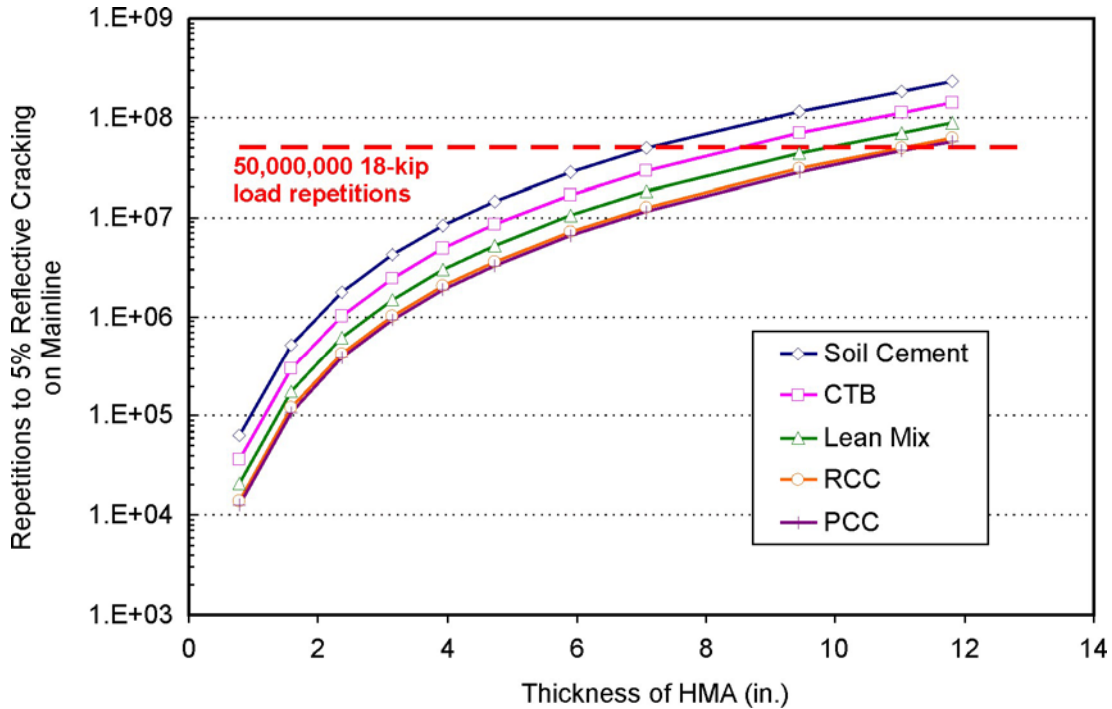


Figure 11. Reflective Cracking Modeling for Various Rigid Bases and HMA Thicknesses

For 50,000,000 ESALs, as the rigidity of the base increased, the number of repetitions to achieve 5% reflective cracking on the HMA overlay decreased. This suggests that using a stiffer base would tend to generate more reflective cracking on the surface. It should be noted however, that the results obtained may differ in the case of the CRCP because the reinforcement will decrease the crack opening. The thickness of the HMA layer has some effect on the retardation of reflective cracking to reach the surface; this is particularly noticeable for thicknesses between 25 and 100 mm (1 and 4 in). In addition, the minimum HMA thickness of 100 mm (4 in) to control reflective cracking is supported by the results in Figure 11, in which the load repetitions to reflective cracking for any HMA thicknesses less than 100 mm (4 in) are significantly reduced.

Economic Analysis

A simplified economic analysis was used to evaluate the feasibility of composite pavement systems. The study consisted of a deterministic LCCA of the agency costs following VDOT LCCA guidelines (VDOT, 2002) and a sensitivity analysis. These guidelines include predefined work schedules for various pavement structures. Four types of pavements were analyzed. The design was based on a typical section of Interstate 81 with an annual average daily traffic (AADT) of 50,000 vehicles and 30% trucks yielding around 67,000,000 ESALs over a 30-year pavement design period. The thicknesses for the typical flexible, rigid (CRCP), and semi-rigid (Composite with CTB) pavements were obtained using the AASHTO 1993 method, whereas the thickness for the composite pavement with CRCP base was based on the mechanistic modeling and analysis in this study. To simplify the analysis, the shoulders were assumed to have the same structural package as the pavement. Table 10 summarizes the thickness of the various layers for the four structural designs considered in the LCCA.

Table 10. Layer Thicknesses in mm (in) of the Pavement Structures used for the LCCA

Layer	Type of Pavement			
	Flexible	Rigid (CRCP)	Composite w/ CTB	Composite w/ CRCP Base
HMA	288 (11.5)	-	225 (9)	175 (7)
CRCP	-	350 (14)	-	-
CTA ^a	-	150 (6)	200 (8)	-
Granular base	200 (8)	-	-	-
CRCP base	-	-	-	200 (8)
Subbase	225 (9)	-	225 (9)	225 (9)

^a Note: CTA = cement-treated aggregate

Table 11 shows the work schedule used in the LCCA for this study. The VDOT (2002) guidelines for the flexible, rigid (CRCP), and semi-rigid (composite with CTB) pavement structures were used. A continuous 10-year functional mill and overlay maintenance activity was assumed for the composite with CRCP base pavement based on the literature (NCHRP, 2004; MDSHA, 2002; Smith et al., 2001).

A 50-year analysis period was used as recommended by VDOT. The unit prices of various items were obtained from the average state bid tabulations published on VDOT’s website (VDOT, 2007). The unit weight values for AC, aggregates, and drainage layer remained unchanged for the volumetric computations. All costs computed were based on a 1-mile road section. The present worth (PW) method was selected to compare all the different pavement alternatives. A discount rate of 4%, as recommended by VDOT and the FHWA, was used.

Table 11. Maintenance and Rehabilitation Schedule for Pavement Alternatives Activities

Year	Type of Pavement			
	Flexible	Rigid (CRCP)	Composite w/ CTB	Composite w/ CRCP Base
0	New construction	New construction	New construction	New construction
10		Pavement maintenance		Functional mill and replace
12	Functional mill and replace		Functional mill and replace	
20		Pavement restoration and HMA overlay		Functional mill and replace
22	Structural mill and replace		Structural mill and replace	
30		Functional mill and replace		Functional mill and replace
32	Major rehabilitation		Major rehabilitation	
40		Pavement restoration and HMA overlay		Functional mill and replace
44	Functional mill and replace		Functional mill and replace	
50	Salvage value	Salvage value	Salvage value	Salvage value

The applicability of the work schedule shown in Table 11 for the composite pavement with CRCP base alternative was verified using the distress prediction curves obtained in the technical analysis. The curves were utilized to estimate the number of years required for a maintenance operation to be triggered because the corresponding distress reach the defined threshold (Figure 12). The numbers of years for each analyzed distress to reach the threshold are summarized in Table 12.

Table 12. Years for Composite Pavement with CRCP Base to Reach Distress Trigger Levels

Fatigue (Bottom-Up)	Fatigue (Top-Down)	Rutting	Reflective Cracking	Proposed Year for Maintenance Activity
50+	50+	~11	~8	10

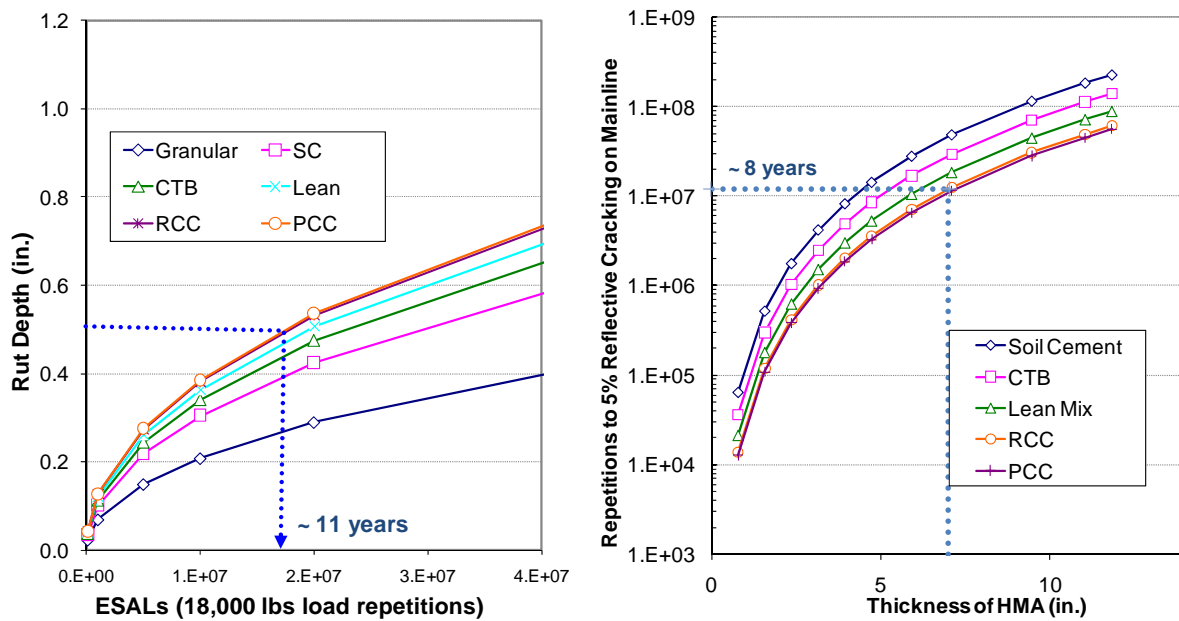


Figure 12. Estimates of Time to Reach Distress Trigger Values

The proposed year for the maintenance activity (10 years) is within the range of the rutting and reflective cracking distresses presented in the table. Although reflective cracking reaches an unacceptable level in 8 years based on the models used, it is important to mention that reflective cracking is highly unlikely due to the absence of longitudinal or transversal joints in the CRCP. On the other hand, rutting in the HMA is more likely to develop, however, the milling and replacing of part of the HMA course every 10 years will correct the rutting before it reaches the unacceptable value. Therefore, for the composite pavement with CRCP base the 10-year functional maintenance frequency recommended by the literature was considered appropriate for the feasibility study. The results of the LCCA are summarized in Figure 13.

According to the LCCA, the least expensive pavement alternative was the composite pavement with a CTB layer. The next least expensive alternative was the flexible pavement, which costs approximate 15% more than the least costly alternative. The composite pavement with a CRCP base layer was the third least expensive alternative, costing approximate y 44% more than the least costly alternative over the life-cycle of the highway. Finally, the rigid CRCP

had the greatest cost of all the pavement alternatives. Several factors contribute to making the composite with CTB the least expensive alternative. The unit price of the cement-treated aggregate (CTA), used to construct the CTB, is \$21.00 per ton, whereas the unit price of a granular base (aggregate 21-B) is \$18.00 per ton. This suggests that the cost of the CTB and granular base layer is similar. Because of this, the main cost is attributed to the HMA layer, which has an average unit price of \$68.00 per ton (\$76.00 for HMA surface mix, \$65.00 for HMA intermediate mix, and \$62.00 for HMA base mix). The savings are due to the reduction of the typical thickness from 288 mm (11.5 in) for flexible pavement to 225 mm (9 in) for the composite with CTB.

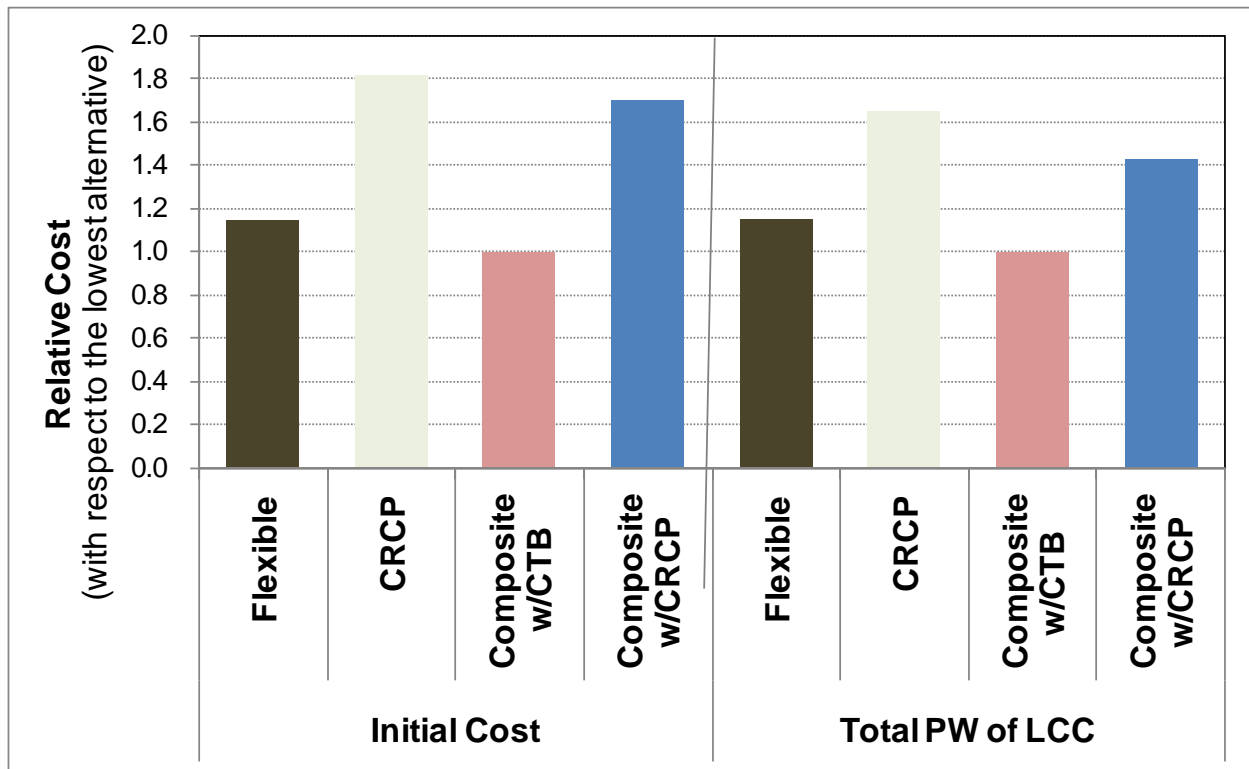


Figure 13. Initial Const and PW Costs for all Alternatives

In the case of the composite pavement with a CRCP base, the cost of the 200 mm (8 in) concrete base (\$81.48 per m² [\$66.00 per sq. yd]) is relatively high. With the computed thickness of the rigid slab using the AASHTO 1993 method for the CRCP pavement alternative, the price per square meter was \$ 104.93 [\$85.00 per sq. yd.], which accounts for the majority of the price difference between the composite pavement with CRCP base and the rigid pavement alternative.

Despite the noticeable difference in the PW costs obtained, there is an important consideration regarding composite pavements. According to the VDOT LCCA publication, a composite pavement with a CTB would be due for a reconstruction when year 50 is reached. However, Balbo and Cintra (1994) conclude that because CTB is originally produced with aggregates (i.e., it contains CTA) the material will behave like a very good granular material.

This suggests that a reconstruction may not be required; milling and replacement of the AC layer would be sufficient. However, reflection cracking is likely to occur. In the case of the composite pavement with CRCP base, a similar assumption can be made because only functional maintenance operations are performed on the asphalt course throughout its service life. In addition, the longevity of such pavement, due to the bituminous surface layer preserving the structure integrity of the base, suggests that reconstruction is not necessary. In brief, typical flexible and rigid pavements reach the end of their service lives after 50 years, at which time a reconstruction is likely to occur; however, composite pavements can last more than 50 years as long as maintenance and light rehabilitation operations are performed.

Sensitivity Analysis

A sensitivity analysis examining the effect of traffic on the PW of agency costs was performed to investigate if the flexible over CRCP composite pavement structure becomes cost effective for very high traffic volumes. This evaluation involved the computation of total agency costs at different traffic volumes. ESALs ranges of 33, 67 and 135 million over the design life were considered.

Traffic growth curves were created for the 50-year LCCA analysis period for each AADT case. Then, the years at which rehabilitation needed to take place on the typical traffic growth curve (i.e., approximately 67,000,000 ESALs) were shifted according to the ESALs required for the same pavement structures to reach a maintenance or rehabilitation trigger (Table 13). The increase in ESALs can be due to an increase in the traffic volume or an increase in the percentage of trucks. A reconstruction was scheduled for the highest traffic alternative in year 35, except for the composite with CRCP base pavement. The present worth computations for all the alternatives using a discount rate of 4% are summarized in Figure 14. It should be noted that the assumed maintenance schedule for the composite with CRCP base pavement was not changed with the increased traffic. This assumption was based on the experiences reviewed in the literature; however, it would need to be verified experimentally before strong conclusions can be drawn.

It can be observed that as the ESALs increase, the PW of all alternatives increase as well, except for the composite with CRCP base which stays at a constant PW throughout. The CRCP base composite pavement remains with a constant PW cost because of the assumption that only periodic functional mill and replace every 10 years is required to accommodate very high volumes of traffic; approximately 400,000,000 ESALs (U.K., 2006). The sensitivity analysis suggests that CRCP base composite pavements have the potential to save significant agency costs when considered for very high-volume high-priority highways (approximately 140 million ESALs or greater).

Table 13. Estimated Maintenance Schedule for Different ESAL Levels

Flexible and Composite with CTB			
ESALs	~33M	~67M	~135M
Functional Mill and Replace	21	12	7
Structural Mill and Replace	35	22	13
Major Rehabilitation	47	32	19
Functional Mill and Replace	-	44	29
Reconstruction	-	-	35
Functional Mill and Replace	-	-	41
Structural Mill and Replace	-	-	47
Rigid (CRCP)			
Concrete Pavement Maintenance	18	10	5
Concrete Pavement Restoration and AC Overlay	33	20	12
Functional Mill and Replace	45	30	18
Concrete Pavement Restoration and AC Overlay	-	40	25
Reconstruction	-	-	35
Concrete Pavement Maintenance	-	-	40
Concrete Pavement Restoration and AC Overlay	-	-	47
Composite with CRCP Base			
Functional Mill and Replace	10	10	10
Functional Mill and Replace	20	20	20
Functional Mill and Replace	30	30	30
Functional Mill and Replace	40	40	40
Salvage Value	50	50	50

Note: All maintenance operations defined in accordance with VDOT (2002).

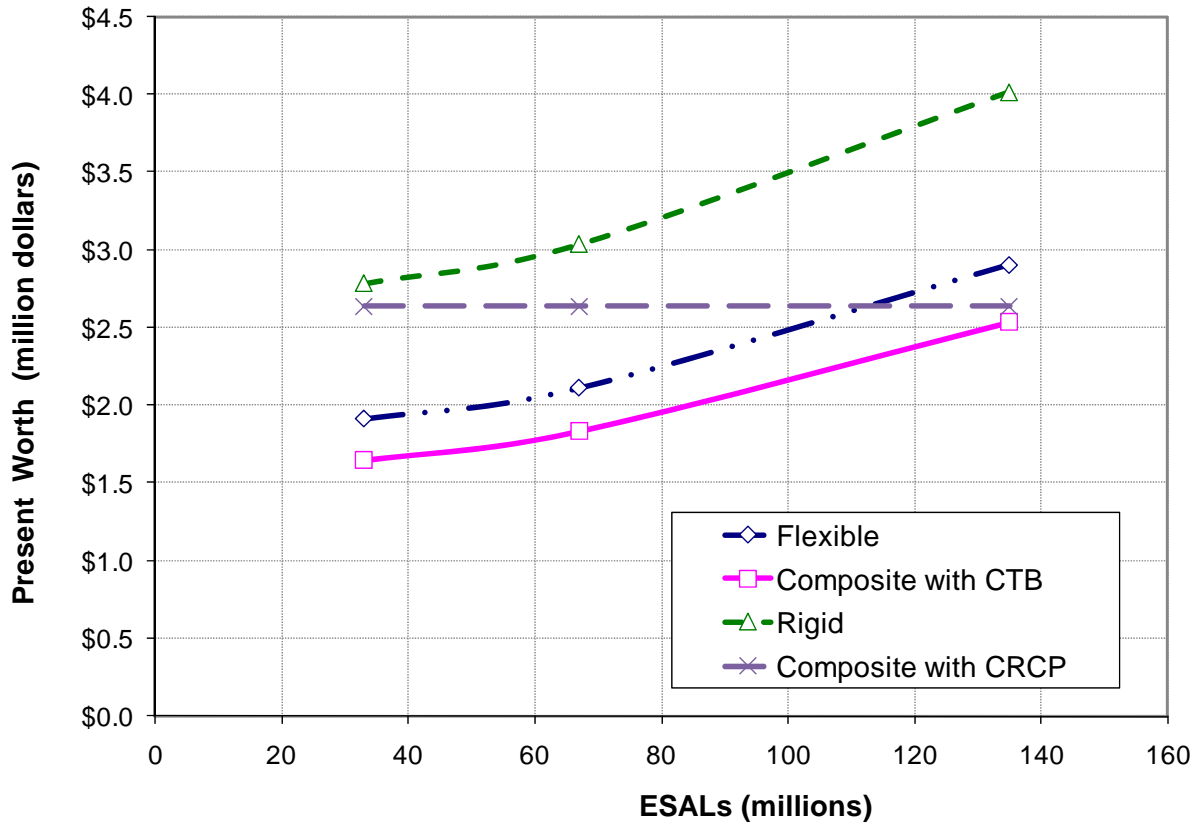


Figure 14. PW Computation of Pavement Alternatives at Different Design ESALs

FINDINGS

The main findings of this study concerning the technical and economic evaluations of composite pavement systems to be used during the PTS process are the following:

- According to the literature, countries (e.g., the U.K., Spain) that have used composite pavement systems in their main road network have had a positive experience in terms of functional and structural performance. The review suggests that this type of pavement can also perform satisfactorily in Virginia. Furthermore, good performance could also be expected from existing CRCP overlaid with high-quality HMA surfaces if the overlay is applied when the existing pavement is still in relatively good condition.
- At the technical level, composite pavements mitigate various structural and functional problems that typical flexible or rigid pavements tend to present. The use of rigid bases minimize (or eliminate) the development of distresses such as HMA fatigue cracking, subgrade rutting, PCC erosion, and PCC loss of friction, among others.
- However, other types of distresses such as reflective cracking and rutting within the HMA layer need to be considered because they affect composite pavement systems more than the traditional pavement structures. Premium HMA surfaces and/or reflective cracking mitigation techniques may be required to mitigate these potential problems. The minimum thickness of the HMA layers to mitigate reflective cracking range from 100 to 200 mm (4 to 8 in). One of the countries with more experience concerning composite pavements is the U.K., which uses an HMA layer thickness of 175 mm (7 in).
- The use of a high-stiffness base layer under the HMA surface course provided the following benefits:
 - Deflections at the HMA surface are significantly reduced as the stiffness of the base layer increases.
 - Fatigue (bottom-up) cracking in the HMA, due to high tensile strain at the bottom of the layer, is greatly minimized; in some cases the number of repetitions to fatigue cracking was determined to be unlimited.
 - Permanent deformations (rutting) due to vertical compressive strains and stresses in the unbound subbase and, most importantly, subgrade layer are significantly minimized.
- On the other hand, permanent deformations within the HMA layer tend to increase as the stiffness of the base increases; however, the use of rut resistant mixes such as SMA may reduce this effect.
- A deterministic LCCA (considering only agency costs) showed that of the composite pavement with CTB can cost less than the traditional flexible and rigid pavement alternatives. Comparing the composite with CTB to the flexible pavement, the

composite alternative requires a lower HMA thickness due to the high support provided by the rigid base.

- A sensitivity analysis of the agency costs over the life-cycle of the pavements, suggests that CRCP base composite pavements can become a cost-effective alternative for very high-traffic high-priority highways (carrying more than approximately 140 million ESALs).

CONCLUSIONS

Composite pavement systems can become a cost-effective pavement alternative during the PTS process for high-volume high-priority highways because of the functional, structural, and economic benefits they can provide during their service life. These types of structures can provide long-life pavement that offers good serviceability levels and rapid, cost-effective maintenance operations. While likely to be more suited for new construction, composite pavements are still relevant for VDOT in that they should be considered for lane addition projects (such as truck climbing lanes) that are expected to carry high traffic volumes and heavy truck loads.

The feasibility-level LCCA suggests that the use of a composite pavement with a CTB can be a cost-effective alternative for a typical Interstate traffic (e.g., 35 million ESALs). Alternatively, composite pavement with CRCP base may become more cost-effective for very high volumes of traffic (approximately 140 million ESALs and greater).

Finally, it is important to note that the maintenance schedule for the CRCP base composite pavements analyzed was determined based on the literature review, and its applicability to Virginia highways should be verified. The costs of reflective cracking mitigation actions were not included in the feasibility analysis.

RECOMMENDATIONS

1. *VDOT's Materials Division should consider composite pavement structures with CTB as one of the alternatives in the PTS process for interstate (or other high volume) highways.* However, appropriate methods should be used to mitigate reflective cracking at the HMA surface.
2. *VDOT's Materials Division should also consider composite pavement structures with a CRCP base for very high traffic highways (carrying approximately 140 million ESALs or greater) due to their relatively low long-term maintenance needs.* Since the CRCP does not have any transversal joints, reflective cracks should not significantly affect the functionality, serviceability, or structural adequacy of the pavement system. For VDOT, the most applicable locations for composite pavements would be areas of total reconstruction or lane additions (such as truck climbing lanes).

COSTS AND BENEFITS ASSESSMENT

As shown in the economic analysis section of this report, the use of composite pavement structures can provide a cost-effective alternative for the construction of high-traffic volume corridors throughout the state. Composite pavement systems mitigate various structural and functional problems that typical flexible or rigid pavements tend to present, such as HMA fatigue, subgrade rutting, PCC erosion, and PCC loss of friction, among others. However, they are also more prompt to develop other types of distresses, such as reflective cracking and HMA rutting.

A life cycle cost analysis considering agency cost showed that composite pavement with CTB can be a cost effective alternative to the typical flexible and rigid pavement systems. The composite pavement systems with CTB require thinner HMA layer than equivalent traditional flexible pavements, which reduces the initial construction costs.

Furthermore the sensitivity analysis of the agency costs over the life-cycle of the pavements, suggest that the CRCP base composite pavements can become a cost-effective alternative for very high-traffic high-priority highways (carrying more than approximately 140 million ESALs). However, this analysis was based on an assumed maintenance schedule determined in accordance with the recommendation of the literature reviewed

In addition to the agency savings, road user cost saving could also be important, specially for the HMA over CRCP composite pavement option because it would not require any lengthy rehabilitation actions, as is the case for the typical flexible and rigid pavements.

ACKNOWLEDGMENTS

This report was produced under the joint sponsorship of the Virginia Tech Transportation Institute, the Virginia Transportation Research Council and the Virginia Department of Transportation. Drs. Linbing Wang and Edgar de León from VTTI contributed to the conception and development of this project. The project technical panel members, Tanveer Chowdhury, Stacey Diefenderfer, Audrey Moruza, Bipad Saha and Thomas Tate, provided valuable guidance, comments, and recommendations.

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**APPENDIX A
SURVEY**

A web-based survey created by the Virginia Transportation Research Council (VTRC) and the Center for Sustainable Transportation Infrastructure at the Virginia Tech Transportation Institute (VTTI) was made available online for 30 days with the objective of assembling a synthesis of the design of composite pavements. The survey was aimed for the departments of transportation (DOT) all over the U.S. The following survey was sent to state DOT pavement design engineers.

SECTION 1 : CONTACT INFORMATION

Name: _____
Current Position/Title: _____
Agency: _____
Address: _____
City: _____ State: _____ Zip: _____
Telephone: _____ Fax: _____
Email: _____

SECTION 2: GENERAL INFORMATION

1. **What is the name (or acronym) of the design method used by your agency/company for *flexible* pavement design?**

2. **What is the name (or acronym) of the design method used by your agency/company for *rigid* pavement design?**

3. **Do you have complementary guidelines to facilitate the use of the design method(s). If so, please send us a copy if possible.**

Yes

No

4. **What is the form of the tools you use for design:**

a. **Paper design guide / nomographs**

b. **Pavement catalogue**

- c. Pavement analysis software
- d. Pavement design software

5. Specify the year in which the current design method was implemented within your organization _____

6. Give an estimated percentage of new roads constructed using:
- a. Flexible pavements _____%
 - b. Composite pavements* _____%
 - c. Rigid pavements _____%

* How much percentage are a result of HMA overlay over existing PCC**
 _____%

** If the percentage of composite pavements is 0%, please skip to the SECTION 5

SECTION 3 : COMPOSITE PAVEMENT DESIGN INPUTS

7. Which environmental factors are taken into consideration in the design method used:
- a. Climatic zone(s)
 - b. Air temperatures
 - c. Pavement Temperatures
 - d. Detailed daily temperature data
 - e. Mean monthly/seasonal/annual temperatures
 - f. Maximum and minimum monthly/seasonal/annual temperatures
 - g. Equivalent monthly/seasonal/annual temperatures
 - h. Precipitation
 - i. Frost index
 - j. Frost penetration depth
 - k. Other(s): _____

8. What kind of traffic input do you use for the design of composite pavements?

- a. Equivalent Single Axle Load (ESAL)
- b. Load spectra
- c. Maximum axle or wheel load

9. What is the design life (in years) that composite pavements are typically designed for in your agency?

- <20 20 25 30 40 50 >50

10. During the Pavement Type Selection (PTS) process for composite pavements, which of the following factors are considered?

- a. Construction costs
- b. Preventive maintenance costs
- c. Rehabilitation costs

- d. **User-related costs (e.g., user delay)**
- e. **Environmental impact**
- f. **Other(s):** _____

11. Do you use *Reliability* as a part of the pavement design process? If so, what level of reliability do you normally consider for designing composite pavements?

- a. **No Reliability is used**
- b. **85%**
- c. **90%**
- d. **95%**
- e. **99%**
- f. **Other:** _____

12. Do you use any other inputs for the design procedure (besides the material properties) not listed above? If so, please describe.

SECTION 4: COMPOSITE PAVEMENT DESIGN CRITERIA

13. What method or design procedure do you use to design composite pavements?

- a. **AASHTO modified method**
- b. **US Navy and Military composite pavement design procedure**
- c. **NCHRP 1-37 – Mechanistic-Empirical Pavement Design Method**
- d. **Illinois Department of Transportation (IDOT) method**
- e. **United Kingdom composite pavement procedure**
- f. **Other:** _____

14. What types of layers comprise *your* typical composite pavement structure?

- a. **Surface (flexible) layer**
 - i. **Dense Graded / Hot-Mix Asphalt (HMA)**
 - ii. **Stone Matrix Asphalt (SMA)**
 - iii. **Open-Graded Friction Course (OGFC)**
- b. **Base (rigid) layer**
 - i. **Jointed Plain Concrete (JPC) pavement**
 - ii. **Continuously Reinforced Concrete (CRC) pavement**
 - iii. **Roller-Compacted Concrete (RCC)¹ pavement**
 - iv. **Lean Mix Concrete²**
 - v. **Cement-Treated Base (CTB)³**
 - vi. **Soil Cement⁴**
 - vii. **Other:** _____

¹ Dry concrete consistency; zero slump; vibratory compaction; compressive strength 4,000 to 10,000 psi; flexural strength 500 to 1,000 psi; modulus of elasticity 3,000,000 to 5,500,000 psi; cement content 9 to 18%.

² Low strength concrete (low cement content); slump 1 to 3 in.; air content 4 to 8%; compressive strength at 7 days 500 psi (minimum), at 28 days 750 to 1,200 psi; cement-aggregate ratio 1:20 to 1:24 in volume.

³ Cement content 3 to 6% (weight); compressive strength at 7 days 650 psi, at 28 days 1,160 psi; modulus of elasticity 250,000 to 1,000,000 psi

⁴ Natural soil modified with 3 to 7% cement content; modulus of elasticity 50,000 to 100,000 psi.

- c. **Subbase**
 - i. **Granular material**
 - ii. **Cement Modified material/soil**
 - iii. **No subbase is used for the design**
 - iv. **Other:** _____
- d. **Subgrade**
 - i. **Cement Modified material/soil**
 - ii. **Natural subgrade compacted**
 - iii. **Other:** _____

15. Are there any minimum thickness requirements for some or all of the layers of the composite structure?

- a. **Surface course** _____ in.
- b. **Base layer** _____ in.
- c. **Subbase** _____ in.
- d. **Subgrade** _____ in.
- e. **No minimum thickness is required**

16. For each of the layers described below, what characteristics are used in the design procedure (please check all that apply):

- a. **Subgrade**
 - i. **California Bearing Ratio (CBR)**
 - ii. **Resilient Modulus (elastic stiffness)**
 - iii. **Frost susceptibility**
 - iv. **Soil type/classification**
 - v. **Gradation**
 - vi. **Other(s):** _____
- b. **Subbase**
 - i. **California Bearing Ratio (CBR)**
 - ii. **Resilient Modulus (elastic stiffness)**
 - iii. **Permeability**
 - iv. **Frost susceptibility**
 - v. **Soil type/classification**
 - vi. **Material strength (unconfined comp. strength)**
 - vii. **Other(s):** _____
- c. **Base (rigid layer)**
 - i. **Cement content**
 - ii. **Flexural strength @ 7th day**
 - iii. **Compressive strength @ 7th day**
 - iv. **Coefficient of thermal expansion**
 - v. **Other(s):** _____
- d. **Surface course (flexible layer)**
 - i. **Elastic Modulus**
 - ii. **Dynamic Modulus**
 - iii. **Rheological properties**

- iv. Coefficient of thermal expansion
- v. Fatigue resistance
- vi. Rutting performance
- vii. Other(s): _____

17. Please specify the typical properties of the following layers in your composite pavement system.

- a. Surface course (flexible layer)
 - i. Asphalt content _____%
 - ii. Air voids (target) _____%
 - iii. Other(s): _____
- b. Base (rigid layer)
 - i. Typical cement content _____%
 - ii. Typical flexural strength @ 7th day _____psi
 - iii. Typical compressive strength @ 7th day _____psi
 - iv. Other(s): _____

18. Is there a design consideration/criteria regarding the mitigation or control of reflective cracking? If so, please describe.

- a. Yes
 - b. No
-

SECTION 5 : CONSTRUCTABILITY

19. Have you used/placed any reflective cracking mitigation technique/method such as Stress Absorbing Membrane Interlayer (SAMI), Microcracking, Pre-Cracking, Geotextiles, etc.? If so, which ones and what has been your experience?

- a. Yes
 - b. No
-

20. If you have used CTB or Soil Cement, where have you prepared this mix:

- a. In the field
- b. In a plant

21. Please describe any issues or challenges that composite pavements brought in your construction.

SECTION 6 : COMMENTS

22. Please comment on any additional information that you believe could help to better the understanding, design, and construction of composite pavements.

APPENDIX B SURVEY RESULTS

The survey created during this study was sent to state DOT pavement design engineers. Responses were received from 34 state DOT's. From these responses, 11 agencies responded as having experience designing composite pavements. Eight responses indicated the experience came from the rehabilitation of existing rigid pavements and 3 of the 11 indicated experience designing new composite pavements. The survey results presented in this appendix are based on the response of all 11 states that have the experience with composite pavement design.

Table B.1. Summarized Survey Results

Transportation Agency	SCDOT	OhioDOT	TxDOT	MDOT	MDSHA	NJDOT
Design method for composite pavements	AASHTO 1993	AASHTO Modified	FPS-19W	AASHTO 1993	AASHTO 1993	AASHTO 1993
New Composite pavements in road network	2	0	4	0	0	0
Typical design life for composite pavements	20	20	20	20	20	20
Reliability used in the design process	No	Yes	Yes	Yes	Yes	Yes
Flexible layer for CPS	HMA	HMA	HMA	HMA	HMA, SMA	HMA, SMA, OGFC
Rigid layer for CPS	CTB	JPCP	CTB	JRCP	JPCP, CRCP	JPCP
Subbase for CPS	Cement modified material/soil, or no subbase	Granular material	No subbase is used	Granular material	No subbase is used	Granular material
Subgrade for CPS	Natural subgrade compacted	Cement modified material/soil, and/or natural subgrade compacted	Lime modified material/soil	Natural subgrade compacted	Natural subgrade compacted	Natural subgrade compacted
Min. thickness for flexible layer (<i>inches</i>)	4	3	2	3.5		
Min. thickness for rigid layer (<i>inches</i>)	6	8	8			
Typical asphalt content	4 to 6%	7%	5%	5 to 6%		5%
Typical air voids (target)	4 to 4.5%	3.5%	4%	4%	4%	4%
Typical cement content	2 to 5%	600 lb	3 to 4%			
Typical compressive strength	600 psi @ 14 days		350 psi @ 7 days			
Design criteria or consideration for reflective cracking	Yes	Yes	Yes	Yes	Yes	Yes
Comments	Their philosophy is to use a low strength cement-treated base material to control shrinkage cracking and place that layer at a relatively high thickness to avoid fatigue cracking.	Their design procedure for composite pavements consists of designing a rigid pavement and then reducing the thickness of the concrete by one inch and add a three inch asphalt surface.	Microcracking of the CTB has been used as a method to retard reflective cracking on the surface course.			Ongoing research has shown Strata and other interlayer mixtures to be effective, binder rich surfaces such as SMA and OGFC perform better than SUPERPAVE, geo-textiles have not been very effective.

Transportation Agency	GaDOT	CODOT	TnDOT	ConnDOT	IowaDOT
Design method for composite pavements	AASHTO 1972	AASHTO 1993	AASHTO 1993	AASHTO Modified	AASHTO 1993
Composite pavements in road network	0	0	2	0	0
Typical design life for composite pavements	20	20	20	20	20
Reliability used in the design process	No	Yes	Yes	Yes	Yes
Flexible layer for CPS	HMA, SMA, OGFC	HMA, SMA	HMA	HMA	HMA
Rigid layer for CPS	JPCP, CRCP	JPCP, CTB, Soil Cement	CTB, Lime Fly-ash	JPCP, JRCP	JPCP, CRCP
Subbase for CPS	Granular material	Granular material, Cement modified material/soil, or no subbase is used.	No subbase design unless soil conditions (CBR less than 3) warrant cement modified soil.	Granular material	Granular material
Subgrade for CPS	Cement modified material/soil, natural subgrade compacted	Cement modified material/soil, natural subgrade compacted	Natural subgrade compacted	Natural subgrade compacted	Natural subgrade compacted
Min. thickness for flexible layer (<i>inches</i>)	5.5		9.25	3	3
Min. thickness for rigid layer (<i>inches</i>)			5		
Typical asphalt content	5%	5.5%	3 to 8%	5%	6%
Typical air voids (target)	7%	4%	4%	4%	
Typical cement content		4%			
Typical compressive strength					
Design criteria or consideration for reflective cracking	Yes	No	No	Yes	No
Comments			A drainage layer is used on top of the rigid base layer.	Requirement: PCC Modulus of Rupture (700 psi), also PCC Elastic modulus (typically 3,500,000 psi)	Modulus of Rupture (MOR) of 650 psi @ 28 days

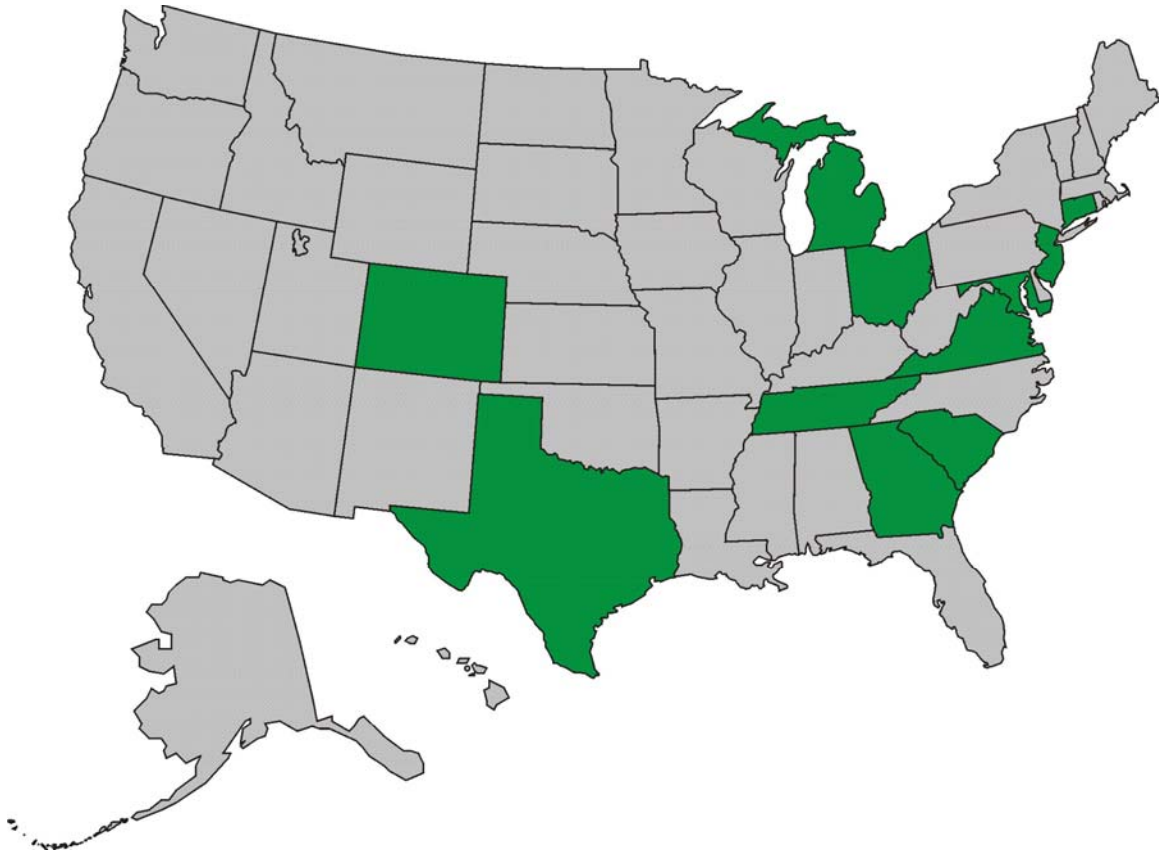


Figure B.2. Survey participants indicating experience with composite pavement design (in green [dark]).

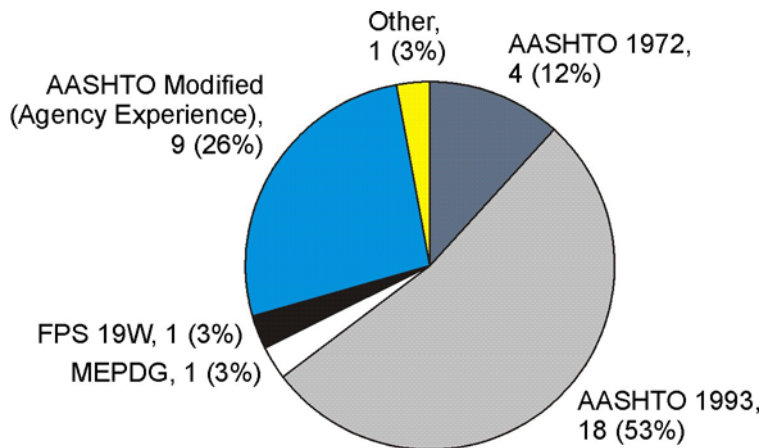


Figure B.3. Response to Question 1, *What is the name (or acronym) of the design method used by your agency/company for flexible pavement design?*

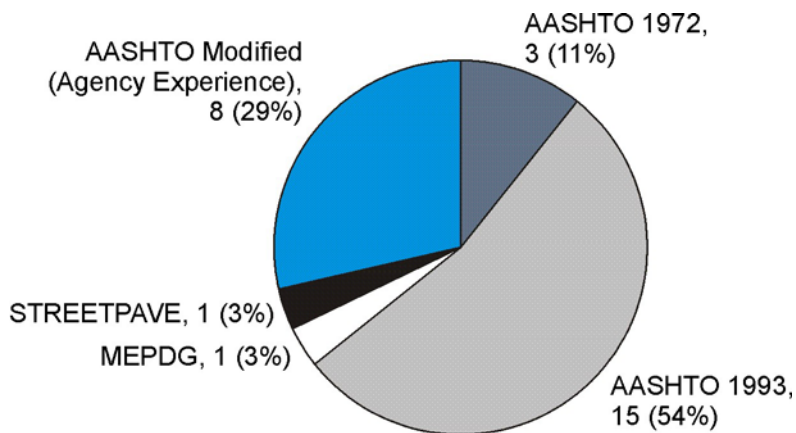


Figure B.4. Response to Question 2, *What is the name (or acronym) of the design method used by your agency/company for rigid pavement design?*

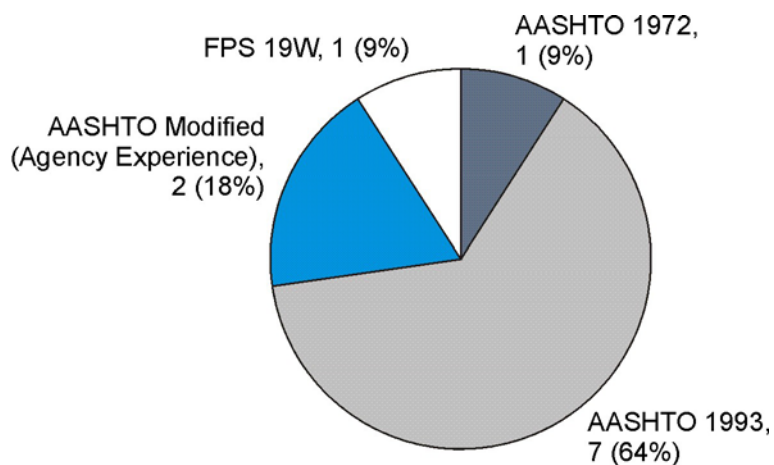


Figure B.5. Response to Question 3, *What is the name (or acronym) of the design method used by your agency/company for composite pavement design?*

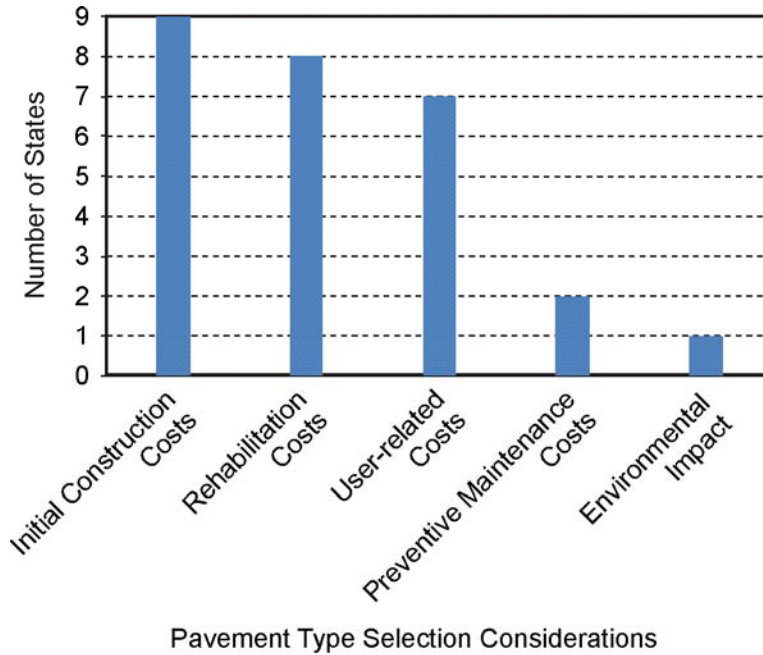
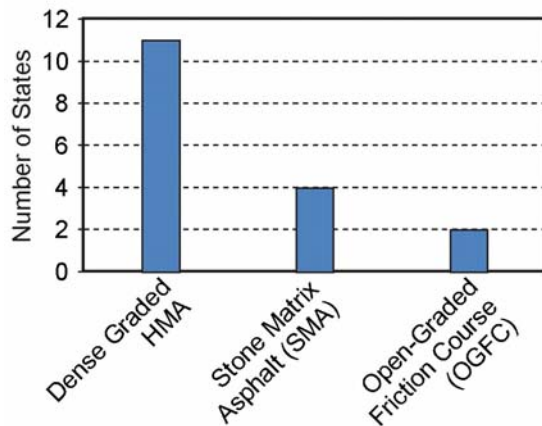


Figure B.6. Response to Question 10, *During the Pavement Type Selection (PTS) process for composite pavements, which of the following factors are considered?*

Flexible Course on the CPS



Rigid Base on the CPS

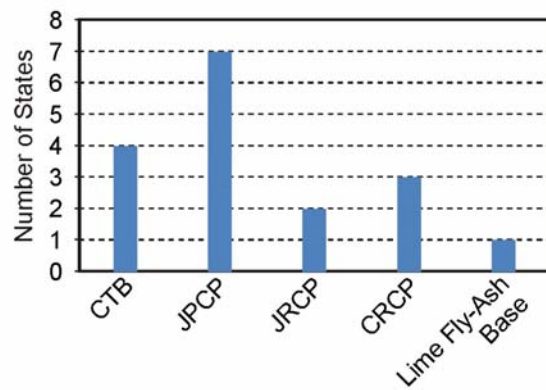


Figure B.7. Response to Question 14, *What types of layers comprise your typical composite pavement structure?*

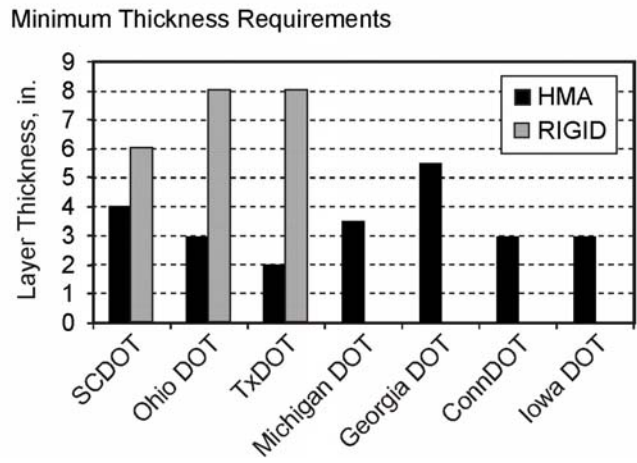


Figure B.8. Response to Question 15, *Are there any minimum thickness requirements for some or all of the layers of the composite structure?*

Survey Comments

The following lists the comments from the survey responses from the 11 states that have some degree of experience with composite pavements:

- *All DOTs* use ESALs as the preferred traffic input parameters for designing composite pavements.
- *TxDOT, SCDOT, and TnDOT* construct new composite pavements (i.e., composite pavements that are not the result of a HMA overlay of an already in-service rigid pavement).
- *MDSHA* is the only transportation agency that recommends the use of a permeable drainage layer on top of the rigid base layer. They state that this permeable drainage layer works well enough, especially when compared to some cases where no drainage layer exists.
- *Most DOTs*—with the exception of CODOT, TnDOT, and IowaDOT—have a design consideration or criteria regarding the mitigation or control of reflective cracking.
- *SCDOT*: Uses a low-strength CTB to control shrinkage cracking and places that layer at a relatively high thickness to avoid fatigue cracking. This results in pavements with very low surface deflections (2-5 mils at 9-kips).
- *Ohio DOT*: Design procedure for composite pavements consists of designing a rigid pavement and then reducing the concrete thickness by one inch and add a three inch asphalt surface course.
- *ConnDOT*:
 - Sawing and sealing performance has been observed to depend on very accurate placement of saw cut (within 2 in. in many cases), and its beneficial effects are higher the thinner the AC layer over PCC.
 - Milling to expose the PCC slab and full-depth repair of PCC joints that are deteriorated in the existing PCC slab is essential to achieving performance in their experience.
 - Have not considered building brand-new composite pavements as the benefits are unclear (beyond perhaps noise reduction).