Long-Life Composite Pavement Systems

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ABSTRACT

The Strategic Highway Research Program 2 (SHRP 2) R21 project on Composite Pavement Systems is under the Renewal area of SHRP 2, the goal of which is to develop a consistent, systematic approach to performing highway renewal that is rapid, causes minimum disruption, and produces long-lived facilities. Two composite pavement design strategies were determined to reflect the SHRP 2 Renewal philosophy of “get in, get out, stay out”:

- High-quality, thin, hot-mixed asphalt (HMA) surfacing (e.g., dense HMA, stone matrix asphalt, porous HMA, asphalt rubber friction course, NovaChip®) over a new, less expensive, portland cement concrete (PCC) structural layer (e.g., jointed plain concrete (JPCP)), continuously reinforced concrete pavement (CRCP), jointed roller-compacted concrete, or lean concrete base/cement-treated base.

- High-quality, thin, PCC surfacing (e.g., exposed aggregate concrete, diamond grinding, conventional texturing) atop a thicker, less expensive, structural PCC layer (e.g., JPCP, CRCP).

Both types of composite pavements have strong technical, sustainable, and economic merits in fulfilling the key goals of the SHRP 2 program including long-lived pavements, rapid renewal, and sustainable pavements. These merits exist because the upper surface requires higher durability materials (which cost more) than the lower PCC portion, which does not require the same quality (or cost). This research investigated the design and construction of new composite pavement systems for all levels of highway and urban streets. The behavior, material properties, and performance for each type of composite pavement under varying climate and traffic conditions were determined. The American Association of State Highway and Transportation Officials Mechanistic-Empirical Pavement Design Guide and other structural, climatic, material, performance prediction models, and design algorithms were evaluated, and some were improved as needed. Practical recommendations for construction specifications and techniques, life cycle costing, and training materials were prepared.

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INTRODUCTION

This paper presents a summary of results from the SHRP 2 R21 project on Composite Pavement Systems. This project is under the Renewal area of SHRP 2, the goal of which is to develop a consistent, systematic approach to performing highway renewal that is rapid, causes minimum disruption, and produces long-lived facilities (Rao et al. 2011).

Types of Composite Pavement Systems

Two composite pavement design strategies were determined to provide both excellent surface characteristics (e.g., low noise, very smooth, nonpolishing aggregates, and durability) that can be rapidly renewed, and long-lasting structural capacity for any level of truck traffic. These two composite pavement design strategies were determined to reflect the SHRP 2 Renewal philosophy of “get in, get out, stay out”:

- High-quality, relatively thin, hot-mixed asphalt (HMA) surfacing (e.g., dense HMA, stone matrix asphalt (SMA), porous HMA, asphalt rubber friction course (ARFC), NovaChip® gap-graded asphalt rubber hot mix) over a new, less expensive, portland cement concrete (PCC) structural layer (e.g., jointed plain concrete pavement (JPCP), continuously reinforced concrete pavement (CRCP), jointed roller-compacted concrete (RCC), or lean concrete base (LCB)/cement-treated base (CTB).

- High-quality, relatively thin, PCC surfacing (e.g., exposed aggregate concrete (EAC), diamond grinding, conventional texturing) atop a thicker, less expensive, structural PCC layer (e.g., JPCP, CRCP).

Both types of composite pavements have strong technical, economical, and sustainable merit in fulfilling the key goals of the SHRP 2 program including long-lived pavements, rapid renewal, and sustainable pavements. A literature and mail survey of U.S. and international highway agencies conducted under SHRP 2 R21 revealed considerable interest in both HMA/PCC and PCC/PCC composite pavements (Rao et al. 2011; Mallela and Von Quintus 2007; Hassan et al. 2008; Cable and Frentress 2004; Green, Nazef, and Choubane 2010; Hall et al. 2007; Bush, Lyles, and Becker 2000; Wojakowski 1998; Fick 2008; Darter 1993; Snell and Snell 2002).

Objectives

The objectives of this research were to investigate the design and construction of new composite pavement systems. The previous technology for the design and construction of new composite pavements was limited. The structural and functional performances of these composite pavements were not well understood or documented. There were no existing mechanistic-empirical performance models of these pavement systems and they need to be developed or improved for use in design, pavement management, and life cycle cost analysis (LCCA). Also, the current construction techniques, guidelines, and specifications were limited or insufficient to properly construct composite pavements.

Composite pavement systems give significant flexibility to the designer to optimize the pavement design in terms of life cycle costs, reduction in future lane closures, and improved sustainability through use of more local and recycled materials. Composite pavements essentially
exhibit the advantages of conventional HMA and PCC pavements while minimizing their disadvantages.

COMPOSITE PROJECTS DESCRIPTION

Experimental composite pavements were constructed at two major research sites, MnROAD/Minnesota Department of Transportation and the University of California Pavement Research Center (UCPRC) at Davis, and were instrumented and monitored under actual climate and heavy traffic loadings. An HMA/JPCP composite pavement was also constructed by the Illinois State Toll Highway Authority north of Chicago, and an EAC/JPCP is planned for the near future. Extensive field surveys were performed in the United States, Canada, and Europe of 64 sections of these two types of composite pavements built on highways with low to very high truck volume. These performance results were utilized in the analysis and validation studies.

MnROAD/Minnesota DOT

Design and Materials: Three sections were constructed. The two sections with PCC top layers were a “high quality” mix containing increased cement content and a high-quality, very durable aggregate (i.e., granite). The aggregate in the top lift was gap-graded and had a maximum size of 0.5 inch (12.7 mm). All basic components of the lower-layer PCC were selected in light of a desire to reduce costs, investigate methods of sustainability, and investigate the reuse of materials into structural components. Higher traffic in the outside lane and lower traffic in the inside lane provided two levels of traffic. JPCP was the basic type of pavement, with transverse joints at 15-ft (4.6 m) intervals and dowels at all EAC/JPCP joints and in the travel lane only for HMA/JPCP joints (Rao et al. 2011; Akkari and Izevbekhai 2011).

Cell 70: This section was 3 inches (75 mm) of HMA over 6 inches (150 mm) of JPCP (50 percent recycled concrete aggregate (RCA)) over an unbound aggregate base course. The inner lane transverse joints included no dowels; the outer lane included dowels. Saw-and-seal of a majority of transverse joints across both lanes for reflection crack control was done, as shown in figure 1.
Cell 71: This section consisted of a 3-inch (75 mm), high-quality, EAC lift over a 6-inch (150 mm), “low cost” RCA (50 percent of RCA) PCC lower lift. Placement of the top EAC over the bottom RCA layer is shown in figure 2. A cross section is illustrated in figure 3.

Cell 72: This section consisted of a 3-inch (75 mm), high-quality, EAC lift over a 6-inch (150 mm), “low cost” (60 percent was replaced with fly ash and inexpensive coarse aggregates), PCC lower lift.
Figure 3. A 3-inch (75 mm), high-quality, EAC lift over a 6-inch (150 mm), “low cost” RCA (50 percent RCA) PCC lower lift.

**Cells 71 and 72 Textures:** (1) Ultra-diamond grinding (Figure 4, left), (2) conventional diamond grinding (Figure 4, right), and (3) EAC achieved by brushing the surface after a proper amount of curing (figure 5).

Figure 4. Ultra-diamond grinding (left) and conventional diamond grinding (right) of the high-quality EAC surface.
Specification development: Full specifications for bidding were developed for each type of composite pavement.

Instrumentation and data acquisition: Thermocouples for measuring temperature throughout the pavement structure; concrete moisture (relative humidity) levels within the slab; static strain for static loads (temperature and moisture changes) generated was measured with vibrating wire (VW) strain gages to provide several critical pieces of information related to the performance of the HMA layer, including the degree of bonding between the HMA layer and the PCC slab, slab curvature, and in-place drying shrinkage and thermal coefficient of expansion; dynamic strain sensors to measure the slab and HMA layer response to loads applied by truck traffic and the falling-weight deflectometer. All data are stored at the MnROAD facility.

Construction: An initial 200-ft (61.0 m) test section for EAC/PCC was constructed and the EAC surface cured and textured. The lessons learned from this test section were invaluable for properly building the main line, which was constructed in May 2010. Main line construction went well with no serious detrimental problems.

Loading and Monitoring: Pavements were opened to Interstate 94 (I-94) traffic in July 2010 and have been loaded ever since except for short closures for monitoring. A full year of heavy traffic has been achieved, and performance over this time is included in this analysis. A photograph of the EAC/JPCP is shown in figure 6.
University of California Pavement Research Center at Davis

**Design:** The composite HMA/JPC pavement has four 12-ft-wide (3.7 m) lanes (A–D), comprised of two HMA mixtures, with two HMA thicknesses (2.5 and 4.5 inches (65 and 115 mm), two PCC thicknesses (5 and 7 inches (125 and 175 mm)), and PCC with and without dowels for load transfer. In each lane (A–D) there are three sections, each consisting of three slabs of 15-ft (4.6 m) length. Each pass of the heavy vehicle simulator (HVS) wheel trafficking covered two transverse joints and one 15-ft (4.6 m) slab in each section (Rao et al. 2011).

**Instrumentation:** A joint deflection measurement device was used to measure absolute vertical movement of PCC slab joints from which the relative movement of the two slabs on each side of the joint can also be measured. A horizontal joint deflection measurement device was used to measure relative horizontal joint movement caused by the opening and closing of PCC slab joints. Thermocouples measured PCC and HMA temperature at various depths. Dynamic strain gages were placed at slab corners and centers and between HMA lifts in the thicker HMA layers to measure strains occurring under the moving HVS wheel, and static strain gages were installed to measure slowly changing PCC strains at the top and bottom of the slab caused by creep, shrinkage, warping, and curling. Moisture sensors were placed in the PCC for bottom and top of slab measurement.

**Construction:** PCC was placed in August 2009 and HMA shortly thereafter. The PCC and two types of HMA both met their respective Caltrans paving specifications. An anionic SS-1h emulsion tack coat was applied. On lanes A and B, the mix placed was a ¾-inch (19 mm) maximum aggregate size dense-graded mix with polymer-modified PG 64-28 binder (PG64-
28PM). On lanes C and D, the mix placed was a ½-inch (12.5 mm) maximum aggregate size mix with gap-graded aggregate and an asphalt rubber binder produced using the “wet process” (RHMA-G).

**Loading and Monitoring:** Loading was accomplished using the HVS for HMA rutting, joint reflection cracking, and PCC slab fatigue cracking, shown in figure 7. The slab-cracking loadings required 200,000 and 320,000 heavy wheel repetitions to be applied on two 5-inch-thick (125 mm) nondoweled slabs with thin and thick HMA, respectively.

![Figure 7. Structural cracking of PCC slab beneath the HMA layer followed by reflection cracking through the HMA layer for section 614HB at UCPRC.](image)

**Illinois State Toll Highway Authority**

HMA/JPCP composite sections were constructed by the Illinois State Toll Highway Authority on two ramps from I-94 to Milwaukee Avenue (off-ramp eastbound direction and on-ramp westbound direction) near Gurnee, Illinois, approximately 40 mi (64 km) north of Chicago. The ramps were constructed in October/November 2010 to emulate best practices of constructing HMA/JPCP composite pavements using recycled aggregate in the PCC slab (Rao et al. 2011).

The project consisted of using stockpiled reclaimed asphalt pavement (RAP) coarse aggregate in the PCC mix with a warm-mix asphalt (WMA) surface layer. The relatively thin (2-inch (50 mm)) high-quality dense-graded WMA layer was placed and bonded to the newly placed 9-inch (225 mm), low-cost, PCC lower lift after the PCC had hardened sufficiently.

- A partial replacement of cement with fly ash (~20 to 25 percent) in the PCC slab. The use of RAP and fly ash offers environmental advantages by diverting the material from the waste stream, reducing the energy investment in processing virgin materials, conserving virgin materials, and minimizing pollution.
- Use of WMA, wherein the mix is heated to a lower temperature (~60 °F to 90 °F (33 °C to 50 °C) reduction) compared to conventional HMA. Lower temperatures mean less fuel
consumption, lower stack emissions, and less fume and odor generation at the plant and job site.

- **PCC mix design:** Coarse aggregate fractionated from the RAP comprised 30 percent of the total coarse aggregate in the PCC mix. Aggregate fines less than 4.75 mm (#4) used in the PCC mix were specified to come from virgin aggregate sources. RAP was fractionated, cleaned, and washed. Up to 15 percent of the total recycled coarse aggregate could consist of agglomerated sand/asphalt particles.

- **The PCC surface was cured and textured after placement to ensure adequate bond with the HMA layer. A tack coat was further sprayed on to ensure bond. The transverse joints were sawed and sealed in the HMA layer over the joints in the JPCP.**

- **The Illinois State Toll Highway Authority has also committed to the construction of a PCC/JPCP composite pavement in the near future.**

### Extensive Field Surveys of 64 Sections Performed in Canada, Europe, and the United States

- **A variety of potential materials for HMA/PCC combinations were identified and surveyed:**
  - Thin asphaltic surfaces include dense HMA, porous HMA, SMA, ARFC, NovaChip, and WMA.
  - Concrete lower layers include JPCP, CRCP, jointed RCC, jointed LCB, and CTB.

- **A variety of potential materials for PCC/PCC combinations were identified and surveyed:**
  - High quality thin concrete surfaces: EAC, higher strength PCC, diamond-ground PCC.
  - Concrete lower layers include JPCP (some with recycled concrete, regular concrete, and lower cost concrete), CRCP.

- **European countries have been constructing new HMA/PCC and PCC/PCC composite pavements for several decades and have substantial experience. HMA/PCC composite pavement was evaluated in the Netherlands using 2 to 3 inches (50 to 75 mm) of porous HMA over CRCP in a dozen major, heavily trafficked projects that are all performing with low noise levels, only minor rutting, and no reflection cracking. Germany has built SMA surfaces on JPCP and most recently over CRCP. One SMA/JPC section was 15 years old under heavy traffic with sawed and sealed joints that had performed well, with only a few joints exhibiting delamination. Austria, Germany, and the Netherlands have all constructed many projects with 2 to 3 inches (50 to 75 mm) of EAC over JPCP since the late 1980s. The entire 200 mi (322 km) of the Austrian A1 freeway across Austria is of this design, with the lower-layer PCC containing recycled concrete and about 10 percent RAP. This highway lies in the harsh climate of the Alps mountain range with lots of snow and ice. None of these sections exhibited significant problems, and they have all performed very well over 20 years.**

- **In reviewing these case studies and discussing the composite pavements with the host engineers and practitioners, a number of benefits to importing and implementing European techniques were identified. Dutch, German, and Austrian researchers claim that**
composite pavements provide similar structural performance as equivalently thick, single-layer pavements at the same price in Europe, yet in addition, the road surface has higher quality and longer life friction and noise reduction due to the high-quality top layer. Furthermore, composite pavements allow for the optimization of costs and materials throughout the pavement cross section:

- High-quality materials can be used in lesser quantities in the upper layer, where they will be of the most benefit to the system.
- Cheaper, lower quality materials can be used in greater quantities and in the lower layer, where they will contribute structurally without detracting from the quality and performance of the overall pavement.

- Studies in Spain provided valuable information on reflection cracking for HMA over RCC and CTB and the forming of joints in the RCC and CTB. In the beginning, the joints were sawed in the beginning, but since 1991, wet-forming of joints has been the method of forming. Long-term results show the effectiveness of wet-formed joints every 8 to 13 ft (2.4 to 4.0 m) in terms of a reduction in joint deflections and high values of joint load-transfer efficiency. The studies also showed that short joint spacing leads to fewer reflection cracks, tighter cracks, and improved performance (Jofre, Vaquero, and Alvarez-Loranca 1998).

**EXAMPLES OF COMPOSITE PAVEMENTS**

Composite pavements have been shown in Europe, the United States, and some in Ontario, Canada, to provide long lives with excellent surface characteristics (low noise, smoothness, and high friction), perpetual structural capacity, rapid renewal when needed, and to utilize more sustainable, lower cost materials in the lower PCC layer. Composite pavements seem to reflect the current direction of many highway agencies to build more economical yet sustainable pavement structures that utilize recycled materials and also make use of locally available materials. Table 1 provides examples of HMA/JPCP and HMA/CRCP composite pavements for a wide range of heavy truck traffic in their first performance period. The field performance of HMA/PCC type of composite pavements is summarized below:

- **Relatively thin asphaltic surfaces** that have performed well include a wide variety of types and thicknesses under heavy traffic: 1- to 2- inch (25 to 50 mm) SMA directly on PCC or on HMA on PCC; 2- to 4-inch (50 to 100 mm) dense-graded HMA over PCC; 1-inch (25 mm) porous HMA over dense HMA/PCC; 1-inch ARFC over PCC projects, 0.625-inch (16 mm) Nova Chip over HMA/PCC. There are several successful thin asphaltic surface courses that perform very well over 10 to 15 years. They do not rut significantly. Transverse joint reflection cracks occurred on all JPCP and RCC pavements with most low to medium severity. Projects in Spain showed that shorter joint spacings (e.g., 10 ft (3.0 m)) result in much less reflection cracking and severity. Dowel bars greatly reduced severity of joint reflection cracks on comparative sections at the MnRoad site. Sawn and sealed joint projects were all in excellent condition and are highly recommended for thin asphaltic surfaces over jointed PCC. Thin HMA or ARFC-type surfaces over CRCP all performed well with no reflection cracking.
• **The JPCP, RCC, and LCB concrete layers** had a wide range of thicknesses from 5 to 14.5 inches (125 to 350 mm), with the thicker sections significantly overdesigned. The RCC ranged from 6 inches to 15 inches (150 to 380 mm) thick (again, much overdesigned). The LCB/CTB ranged from 6 to 11 inches (150 to 275 mm). None of the JPCP, RCC, LCB/CTB, or CRCP showed any transverse fatigue cracking except the 2-inch (50 mm) HMA over 5-inch (125 mm) JPCP in Minnesota under heavy traffic.

• **The CRCP layers** show a wide range of thicknesses, from 8 to 13 inches (200 to 330 mm) with from 0.55 to 0.70 percent reinforcement. The only section with punchouts was a section in Arizona with a low percentage of steel and a 0.5-inch (13 mm) ARFC under very heavy traffic over 16 years, which is not considered an adequate design.

• **Joint spacing for JPCP** typically ranged from 15 to 30 ft (4.6 to 9.1 m). Joints were usually cut in RCC at 15- to 45-ft (4.6 to 13.7 m) intervals. Based on other experimental sections in Spain, the shorter joint spacings (e.g., 10 ft (3.0 m)) were greatly beneficial in reducing the severity and amount of transverse reflection/shrinkage cracking through the HMA. Sawing and sealing joints was also greatly beneficial in controlling the severity of the cracks in thin asphaltic surfaces.

• **Dowels** were used on many, but not all, heavily trafficked JPCP sections. No dowels were used with RCC or LCB/CTB. Reflection cracks dramatically showed the benefits of dowel bars to control joint load transfer efficiency and thus a large reduction in HMA deterioration over the joints.

• **Truck traffic** ranged from low to very heavy. The following ranges existed in units of trucks per year in the heaviest travel lane:
  - Interstates and freeways: 1.4 million trucks / year (0.5 to 3.6 range).
  - Highways: 0.2 million trucks / year (0.1 to 0.3).
  - Local streets: 0.05 million trucks / year (0.004 to 0.08).

• **Total trucks in the design lane** ranged up to 47 million, and the age ranged to 45 years.

• **One section had a total life of 45 years**, during which the asphaltic surface was replaced three times but the PCC did not require any repair. This and another similar HMA/JPCP are expected to carry traffic perpetually into the future with no fatigue cracking, thus no slab replacements and more rapid renewal. In fact, fatigue cracks developed only on the exceptionally thin PCC layers on some experimental sections. None of the JPCP of typical thicknesses developed any slab fatigue cracking.
Table 1. Examples of HMA/PCC Composite Pavements in First Performance Period

<table>
<thead>
<tr>
<th>Composite Pavement; Age/Trucks</th>
<th>Surface Characteristics</th>
<th>Base Slab Characteristics</th>
<th>Performance &amp; Maintenance</th>
<th>Design, Sustainability &amp; Life Cycle Cost (LCC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARFC/JPCP I-10, AZ 17 years &amp; 20 million (M) trucks</td>
<td>1-in. ARFC</td>
<td>14-in. JPCP 15-ft joints Dowels</td>
<td>Excellent performance Transverse joints reflected low severity Smooth ARFC last 20 years No PCC cracks or repairs</td>
<td>DARWin-ME requires thinner slab design Low LCC over many years No lane closures</td>
</tr>
<tr>
<td>SMA/JPCP A93, Germany 13 years &amp; 47 M trucks</td>
<td>1.2-in. SMA, saw &amp; seal joints</td>
<td>10.3-in. JPCP 16-ft joints Dowels</td>
<td>Good performance Transverse joints saw &amp; seal Smooth No PCC cracks SMA debonding repair</td>
<td>DARWin-ME gives same slab design Low LCC Few lane closures</td>
</tr>
<tr>
<td>HMA/CRCP I-10, San Antonio, TX; 25 years &amp; 24 M trucks</td>
<td>4-in. HMA</td>
<td>12-in. CRCP HMA base</td>
<td>Excellent performance No reflection cracks Smooth No punchouts No maintenance</td>
<td>DARWin-ME gives thinner slab design Low LCC over many years No lane closures</td>
</tr>
<tr>
<td>HMA/RCC White Road. Columbus, OH; 7 years &amp; 70,000 trucks</td>
<td>3-in. HMA Sealed cracks after cracking</td>
<td>8-in. RCC 45-ft joints No dowels</td>
<td>Excellent performance Reflection cracks sealed just after cracked Smooth No maintenance</td>
<td>DARWin-ME gives thinner slab design Short joint space Low LCC No lane closures</td>
</tr>
<tr>
<td>HMA/JPCP I-94 MN 1 year &amp; 600,000 trucks</td>
<td>3-in. HMA Saw &amp; seal joints</td>
<td>6-in. JPCP 15-ft joints Dowels</td>
<td>Excellent performance Sawed &amp; sealed transverse joints good condition No PCC cracks Smooth No maintenance</td>
<td>DARWin-ME gives same design PCC contains 50% RCA &amp; 60% fly ash</td>
</tr>
</tbody>
</table>

Note: Trucks given for heaviest lane, one direction only. 1 in. = 25.4 mm; 1 ft = 0.305 m.

Table 2 shows examples of HMA/JPCP sections that have been through two and three HMA surface replacement cycles that were done rapidly since none of the underlying JPCP slabs were cracked and needed replacement. These and other HMA/PCC composite pavements have performed well over many years, with only the rapid replacement of the HMA-type surface course required. They have shown a long life with minimal fatigue damage.
Table 2. Examples of Long-Life HMA/PCC Composite Pavements Over Several Performance Periods

<table>
<thead>
<tr>
<th>Composite Pavement; Age/Trucks</th>
<th>Surface &amp; Rehabilitation</th>
<th>Base Slab Characteristics</th>
<th>Performance &amp; Maintenance</th>
<th>Design, Sustainability &amp; LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA/JPCP I-5, Seattle, WA; 45 years &amp; 35 million (M) trucks</td>
<td>4-in. HMA original; 2-in. 13-years; 2-in. 16-years; 2-in. 11-years; (some milling at times of resurfacing)</td>
<td>6-in. PCC No joints No dowels</td>
<td>Excellent performance; transverse cracks at 70-ft intervals reflected medium severity after 8 years; smooth. Replaced HMA at 11- to 16-year intervals; no additional transverse cracks; no PCC repairs.</td>
<td>DARWin-ME would design thicker slab, add doweled transverse joints at 10 to 15 ft; saw &amp; seal would extend life; LCC low over many years; few lane closures for rehabilitation.</td>
</tr>
<tr>
<td>HMA/JPCP I-294, Chicago, IL; 19 years &amp; 30 M trucks</td>
<td>1992: 3.5-in. HMA original; 2001: Milled off and added 3-in. HMA; no further rehabilitation after 10 more years</td>
<td>12.5-in. JPCP; 20-ft joint spacing; Dowels</td>
<td>Excellent performance; transverse joints reflected medium severity; smooth. Replace HMA at 9- to 10-year intervals; no transverse fatigue cracks in JPCP; no PCC repairs.</td>
<td>DARWin-ME gives thinner slab design, shorter joint spacing; saw &amp; seal joints would extend life; low LCC over many years.</td>
</tr>
</tbody>
</table>

Note: Trucks given for heaviest lane, one direction only.

Table 3 provides examples of PCC/JPCP composite pavements for freeways with heavy truck traffic. These and other PCC/JPCP composite pavements have performed well over many years with only the eventual renewal of the EAC type surface course required through diamond grinding. A summary of the performance of PCC/PCC type of composite pavements is provided.

- **Relatively thin, high-quality concrete surfaces** include a variety of types and thicknesses:
  - The 2- to 3-inch (50 to 75 mm) PCC over JPCP performed well for 18+ years under very heavy traffic. No debonding of PCC from lower-layer PCC was observed, with the exception of some spalling from apparent debonding at the transverse joints of the I-75 Michigan project after 18 years.
  - The 3-inch (75 mm) higher strength PCC over JPCP performed well for 30+ years in Florida. No debonding of the PCC has occurred.

- **The JPCP concrete lower layers** had a range of thicknesses from 6 to 9 inches (150 to 225 mm). None of the JPCP showed any transverse fatigue cracking.
  - Joint spacing for JPCP ranged from 15 to 20 ft (4.6 to 6.1 m).
  - Dowels were used on all of these sections as most were heavily trafficked. As a result, joint faulting was not significant.
Table 3. Examples of PCC/PCC Composite Pavement Characteristics, Applications, and Performance

<table>
<thead>
<tr>
<th>Composite Pavement; Age/Trucks</th>
<th>Surface Characteristics</th>
<th>Base Slab Characteristics</th>
<th>Performance &amp; Maintenance</th>
<th>Design, Sustainability &amp; LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAC/JPCP I-75, Detroit, MI 18 yr; 72 million (M) trucks</td>
<td>2.5-in. EAC</td>
<td>7.5-in. JPCP 6-in. LCB 15-ft joint spacing; Dowels</td>
<td>Fair performance; No transverse fatigue cracking; No joint faulting; Smooth; Only distress is joint spalling or debonding</td>
<td>Designed for very heavy traffic; Low expected LCC; Few lane closures</td>
</tr>
<tr>
<td>PCC/JPCP FL-45, FL 30 yr/; 5 M trucks</td>
<td>3-in. PCC</td>
<td>9-in. JPCP Lower PCC Strength A, B, and C; 15 &amp; 20-ft joint spacing; Doweled &amp; nondoweled</td>
<td>Excellent performance all sections; Low transverse fatigue cracking; Low joint faulting; Long life, low LCC</td>
<td>Pavement somewhat overdesigned; Low LCC; No lane closures over 30-yr; Savings of cement; Good sustainability</td>
</tr>
<tr>
<td>EAC/JPCP A93, Germany 13 yr; 53 M trucks</td>
<td>2.8-in. EAC</td>
<td>7.5-in. JPCP 16.4-ft joint spacing; Dowels; Tied PCC shoulders</td>
<td>Excellent performance; No transverse fatigue cracking; No joint faulting; Smooth; Low noise; Pavement should last many more years</td>
<td>Designed for very heavy traffic; Low LCC; No lane closures Good sustainability</td>
</tr>
<tr>
<td>EAC/JPCP A1, Austria 14 yr; 47 M trucks</td>
<td>2-in. EAC</td>
<td>7.9-in. JPCP (RCA materials) 18-ft joint spacing; Dowels ATB</td>
<td>Excellent performance; No transverse fatigue cracking; No joint faulting; Smooth; Low noise Pavement should last many more years</td>
<td>Designed for very heavy traffic; Low LCC; No lane closures Good sustainability</td>
</tr>
<tr>
<td>PCC/JPCP K-96, Kansas 14 yr; 2.1 M trucks</td>
<td>3-in. PCC</td>
<td>7-in. JPCP 15-ft joint spacing; Dowels PCC shoulders</td>
<td>Excellent performance new pavement; No distress; Smooth;</td>
<td>Pavement over designed; low expected LCC; No lane closures</td>
</tr>
<tr>
<td>EAC/JPCP N279, The Netherlands 8 yr; 11.9 M trucks</td>
<td>3.5-in. EAC</td>
<td>7-in. JPCP 15-ft joint spacing, Dowels</td>
<td>Excellent performance; No transverse fatigue cracks; Smooth; Low noise; No other distress</td>
<td>Well designed; low expected LCC; No lane closures</td>
</tr>
<tr>
<td>EAC/JPCP I-70, Kansas 4 yr; 3 M trucks</td>
<td>1.5-in. PCC 8 different surface textures</td>
<td>11.8-in. PCC 15-ft joint spacing, Dowels PCC shoulders</td>
<td>Excellent performance new pavement; No distress; Smooth; Low noise; Long life expected</td>
<td>Designed for very heavy traffic; Low LCC expected</td>
</tr>
<tr>
<td>EAC/JPCP I-94, Minnesota 1 yr; 600,000</td>
<td>3-in. EAC</td>
<td>6-in. JPCP 15-ft joint spacing,</td>
<td>Excellent performance; No transverse fatigue cracks; Smooth; No maintenance</td>
<td>DARWin-ME gave this design for 15-yr life. PCC 50% RCA, 60% fly</td>
</tr>
<tr>
<td>trucks</td>
<td>Dowels</td>
<td>ash; Good sustainability</td>
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Note: Trucks given for heaviest lane, one direction only.

- **Truck traffic** ranged from medium to very heavy. Typically the following ranges existed in units of trucks per year in the heaviest travel lane:
  - Interstates and freeways: 3.3 million trucks / year (1.8 to 4 range).
  - Highways: 0.3 million trucks / year (0.1 to 0.7).

  Practically none of the PCC/JPCP slabs showed any transverse fatigue cracks.

- **Total trucks in the design lane** ranged up to 72 million, and the age ranged up to 30 years.

### PERFORMANCE MODELING

#### AASHTO MEPDG and DARWin-ME

The AASHTO MEPDG design procedures for HMA overlay of JPCP and CRCP and bonded PCC overlay of JPCP and CRCP were found to be by far the most comprehensive and applicable for design of “new” composite pavements (NCHRP 2004). However, neither the MEPDG nor DARWin-ME includes “new” composite pavements directly as a design alternative. Through use of appropriate inputs, the “Overlay” procedures can be used to design “new” composite pavements. The inclusion of “new” composite pavements into DARWin-ME has been recommended to AASHTO. Extensive testing and evaluations were performed, and many bugs related to composite pavements as well as significant improvements were identified and fixed in the MEPDG prior to the completion of DARWin-ME.

The structural fatigue damage and cracking models for both types of composite pavement were validated using all available data: MnROAD test sections, UCPRC test sections, and the existing 64 sections located in the United States, Canada, and Europe (Netherlands, Germany, Austria). The validation of the DARWin-ME PCC field fatigue curve is illustrated in figure 8 for two slabs tested under full-scale loading at UCPRC test facility. Each slab cracked bottom-up at a cumulative fatigue damage of approximately 1.0 as predicted. Thus, the two field data points fit in agreement with the nationally calibrated field concrete fatigue curve.
Figure 8. DARWin-ME-predicted cumulative damage for UCPRC test cells 613HB and 614HB vs. cumulative load repetitions. The HMA/PCC slabs at the two test cells cracked after approximately 195,000 and 320,000 load repetitions, respectively.

Figure 9 shows the measured fatigue transverse cracking versus damage curve for all HMA/JPCP composite pavements. The field data from HMA/JPCP composite pavements match well with the national calibration curve for JPCP (Darter et al. 2006; NCHRP 2008).

Figure 10 shows the fatigue cracking versus bottom damage curve for the PCC/PCC composite pavements. The field data from PCC/PCC composite pavements match well with the national calibration curve for JPCP (Darter et al. 2006).

It is noted that HMA/CRCP composite pavement also showed good fit with the nationally calibrated model. Both of these plots show that the composite pavement fit well into the nationally derived curve under NCHRP 1-37A and 1-40D (Darter et al. 2006).

These results indicate that the mechanistic modeling in DARWin-ME is reasonably modeling composite pavements. These results do not mean that slab thickness will be the same for conventional or two-layer composite pavements, however.

1. Various other structural and performance models for key distresses (e.g., rutting, joint faulting, International Roughness Index values) in new composite pavements were validated.
2. Several detailed MEPDG design examples for composite pavements were prepared for guidance purposes. Comparisons of several examples with conventional JPCP or CRCP indicated a reduction of 1 to 3 inches (25 to 75 mm) in required thickness for composite pavement. This reduction for HMA/JPCP or CRCP was due to a reduction in temperature gradients. For PCC/JPCP, it was due to the higher strength of the top PCC layer.
3. Detailed recommended revisions to incorporate composite pavements into the MEPDG/DARWin-ME Manual of Practice for consideration by AASHTO.
4. Life cycle cost analysis guidelines and examples. The life cycle costs for composite pavement can be lower than conventional HMA or PCC pavements in various situations where the designer will make the effort to optimize the pavement design.

Figure 9. Fatigue damage versus measured transverse fatigue cracking (mid-slab) for all HMA/JPC or HMA/RCC composite pavements over their service life compared to the existing JPCP national calibration curve (derived in 2007 and used in the current version of DARWin-ME).

Figure 10. Fatigue damage versus measured transverse fatigue cracking (mid-slab) for all PCC/JPC composite pavements over their service life compared to the existing JPCP national calibration curve (derived in 2007 and used in the current version of DARWin-ME).
Use of the AASHTO MEPDG (Version R21) and DARWin-ME to Design HMA/JPCP (including jointed RCC or LCB) or HMA/CRCP

The use of HMA surface reduces the thermal gradient and moisture gradient through the slab, thereby insulating the PCC slab from both temperature and moisture gradients. This has major implications regarding reduction of stresses at top and bottom of the slab and resulting reduced fatigue damage especially at the top of the slab. Comparative designs show significant reduction in composite slab thickness.

- In urban areas with high congestion and costs of lane closures, rapid renewal is paramount. HMA/PCC can be designed for the PCC to last structurally over long time periods (if durable materials are used). The thin HMA can be milled and replaced rapidly with minimal disruption to traffic. PCC/PCC has a much longer surface life, but when needed, the surface can be diamond-ground to rapidly restore smoothness and friction and reduce pavement-tire noise.

- Where high-quality aggregates for PCC are not available (or expensive due to long haul distances), local PCC aggregates may be susceptible to polishing and other durability-related distresses. In these situations, HMA or PCC surfaces can protect the structural integrity of the PCC and can be milled and diamond-ground and rapidly renewed as needed.

- Many urban areas and some rural areas exist with old PCC pavements that can be removed and processed and recycled directly back into lower layer PCC. This provides excellent improved sustainability opportunities for composite pavements.

- Where low pavement noise is required, such as in urban areas with large populations in close proximity to the pavements, porous HMA surfacing of PCC provides the lowest level of noise measured for HMA/PCC. An alternative was discovered at the MnROAD site, where next-generation diamond-grinding was performed on the EAC surfacing, and measurements showed the lowest noise concrete surface ever measured. These surfaces can be renewed rapidly into the future as needed.

- Arizona has built many miles of major freeways with porous rubberized asphalt surface over new JPC and CRC to minimize noise. Low noise is a major reason why porous HMA/PCC and EAC/PCC composite pavements are constructed in European countries.

- Where conventional HMA pavements exhibit transverse cracks and deterioration of transverse cracks are a problem, HMA/CRC is a good alternative to eliminate reflection of transverse cracks. No low-temperature transverse cracks were observed in HMA/JPCP or HMA/CRCP. No longitudinal wheel path cracks have been observed in HMA/PCC pavements either.

- Widening existing PCC or HMA/PCC pavement such that the widened section is structurally compatible with the existing pavement. Both the new and the existing lanes are typically covered with one or more lifts of HMA.

The HMA/JPCP or RCC and HMA/CRCP can be designed using the HMA overlay alternative in DARWin-ME. All improvements were made to the MEPDG prior to the new DARWin-ME software being finalized. However, all of the improvements were not made for PCC/PCC composite pavement. A new version of the MEPDG (R21 Version) was developed to use the
“bonded PCC over JPCP” project to simulate newly constructed PCC/PCC and address the limitations of the existing structural and environmental models for PCC/PCC.

CalME

The UCPRC has been developing a mechanistic-empirical pavement design method for Caltrans. The software associated with the pavement design methodology is termed CalME. CalME rutting and reflection cracking models were evaluated for the SHRP 2 R21 project. Both the rutting model and the reflective cracking simulation follow the incremental-recursive approach. The CalME rutting prediction models were calibrated using the results of the HVS and MnROAD test sections, while the CalME reflection cracking model was tested using the results of some of the HVS test section. Although the number of test cells used in the calibration was small, the results show that measured performance can be effectively predicted with CalME models for all the test cells using average calibration coefficient values. A sensitivity analysis of the CalME reflection cracking and rutting models was performed to evaluate the effects of climate, traffic, HMA mix type, aggregate base stiffness, crack spacing, and HMA thickness. The sensitivity analysis showed that HMA mix type is the primary factor that affects both rutting and reflection cracking (Kohler 2006).

Lattice Model for PCC/PCC Bonding

Extensive work was performed to more fully develop and utilize lattice models for composite slab simulations for debonding of the top PCC layer from the bottom PCC layer. Completed models coupled the lattice models with finite element models to provide a comprehensive model of the PCC/PCC interface bonding. For model simulations of realistic paving conditions in which newly constructed PCC/PCC pavements are placed in a reasonable time frame, debonding of the layers did not occur. Furthermore, additional simulations of layer behavior took into account unrealistic extreme thermal gradients and highly reduced shear strengths at the interface, and these simulations found failure at the interface in only the most extreme of cases, which would not be encountered in the field. This conclusion is supported by observations from the European PCC/PCC experience, as consultants to the R21 project were unable to cite an instance of PCC/PCC debonding. Based on these observations and model simulations, it was the assessment of the research team that debonding is only a concern in PCC overlays of existing PCC pavements, which was outside the scope of the SHRP 2 R21 project (Bolander 2005, 2008).

Recommendations for Composite Pavement Design

Based in part upon these models and improvements made to the MEPDG/DARWin-ME software, the following can now be utilized in design of “new” composite pavements:

- “Newly constructed” HMA/JPCP, HMA/jointed RCC or LCB, and HMA/CRCP can be designed using the AASHTO DARWin-ME software by using the “Overlay” procedure and appropriate inputs with zero past damage.
- PCC/JPCP and PCC/CRCP can be designed using the R21 Version of MEPDG, which includes modifications to the allowable PCC layer thicknesses, representative PCC layer properties, slab and base interaction properties (full versus zero friction), PCC/PCC
subgrade response modeling, and the proper distribution of the temperature nodes representing a thermal gradient through the composite pavement.

Recommendations are provided for inputs and modifications to the DARWin-ME software user interface for design of both types of “new” composite pavements. Revisions for the inclusion of composite pavements in the AASHTO Manual of Practice are provided in detail.

DEVELOPED PRODUCTS

The products from this research can be classified into the following categories: design, construction and materials, and other products.

Design Products

Two key design products were developed for the two types of composite pavements:

- **PCC/JPCP, PCC/CRCP: R21 Version of MEPDG.** MEPDG Version R21 was prepared that includes modifications to the allowable PCC layer thicknesses, representative PCC layer properties, slab and base interaction properties (full versus zero friction), PCC/PCC subgrade response modeling, and a proper distribution of temperature nodes through the composite pavement system. Many of these revisions specifically targeted the Enhanced Integrated Climatic Model used by the MEPDG. This program has been provided to AASHTO for consideration to incorporate the improvements into the DARWin-ME software. The current version of AASHTO DARWin-ME does not include the significant PCC/PCC modifications at this time.

- **HMA/JPCP, HMA/CRCP: DARWin-ME (contact AASHTO).** Many bug fixes and improvements related to HMA/JPCP and HMA/CRCP types of composite pavements were made to the MEPDG software throughout the R21 contract (e.g., crack opening error in HMA/CRCP) and all of these modifications have been already incorporated into the DARWin-ME software. Therefore, the DARWin-ME software can be utilized under the “Overlay” mode to design this type of new composite pavement.

Construction and Materials Products

Construction specifications and guidelines were developed as part of construction at MnROAD and UCPRC for use by agencies considering constructing new HMA/PCC and PCC/PCC composite pavements. These include two-lift, wet-on-wet construction of PCC/PCC pavements, timing and sequencing of operations, texturing procedures and related guidelines, guidelines for paving the stiffer lower lift PCC and the thin upper lift, saw-cutting of joints, and the challenging exposed aggregate brushing technique. The MnROAD construction also involved the use of ultrasonic tomography to nondestructively assess PCC/PCC layer thicknesses and bond quality at the PCC/PCC and slab/base interfaces. Diamond grinding of the PCC upper layer using the next-generation grind that produced such a smooth and quiet surface is included.
Material specifications include those for recycled aggregate, cementitious materials such as cement and fly ash, aggregate type and gradation for EAC, and retarding/curing compound. Procedural specifications include those related to wet-on-wet construction, timing of paving operations, texturing, saw-cutting, sealing of saw and seal joints, tack coat application for HMA/PCC, etc.

Concrete freeze-thaw durability is always a major concern for pavements. The upper layer PCC mixture will experience the most freeze-thaw cycles, but the lower layer mixtures will experience freeze-thaw cycles as well. The RILEM CIF concrete freeze-thaw standard was adopted based upon European PCC-PCC experience, and the equipment was imported from Germany for the SHRP 2 R21 RILEM CIF tests. The CIF test evaluates the capillary suction, surface scaling resistance, and internal damage of concrete samples exposed to 3 percent by volume sodium chloride solution and freeze-thaw cycles, whereas ASTM C666 evaluates the internal freeze-thaw damage of concrete submerged in water and ASTM C672 evaluates the freeze-thaw scaling resistance of concrete exposed to 4 percent sodium chloride solution. RILEM CIF freeze-thaw testing and evaluations were conducted on the concrete mixtures used at MnROAD including EAC, RCA, and low-cost concrete (Setzer 1997, 2009).

All of these concrete mixtures adequately resisted surface scaling and internal damage (modulus) due to frost action. Compared to the decrease in relative modulus of other concrete samples studied with the RILEM CIF procedure, the loss of scaled material and the decrease in relative moduli of all of the samples were relatively small. The lack of scaling and internal damage in both the RCA and low-cost concrete mixtures after 56 freeze-thaw cycles indicated that these mixtures are suitable for use in long-life concrete pavements despite containing recycled concrete aggregates or having a 60 percent cement replacement with fly ash, respectively. It was expected that the EAC concrete samples would experience minimal scaling and internal damage due to frost action because of 1) the high cement content and low water-to-cement ratio of the mix and 2) the use of high-quality granite aggregates (Rao et al. 2011).

**Other Products**

Training products include materials to promote the use and accelerate the adoption of new composite pavements. The training materials will include both design (MEPDG, LCCA) and construction (procedures, guidelines) materials. Also included are Microsoft PowerPoint® presentation materials. Design examples of both major types of composite pavements are included.

A database of test sections includes material properties, performance, traffic, structure, and location (all inputs required for the MEPDG/DARWin-ME) of the 64 sections surveyed for R21. Note that the European Report has been completed and has been published by SHRP 2 online (http://www.trb.org/Publications/Blurbs/163693.aspx).

Three test sections (two PCC/PCC and one HMA/PCC) were constructed at MnROAD with various surface textures (exposed aggregate, conventional grind, next-generation grind, HMA) and design features (doweled/nondoweled and with/without sawed-and-sealed joints for HMA/PCC) with two different PCC mixes in lower lift. These are the only instrumented, inservice, composite pavement test sections in existence. The instrumentation includes static and
dynamic gages, moisture gages, and temperature gages, all of which are wired into a data acquisition unit for continuous collection of data.

**Instrumented MnROAD test sections.** As part of the R21 research, three full-length, two-lane test sections were constructed at MnROAD in Albertville, Minnesota, on I-94. These sections were constructed in April/June 2010 and were opened to traffic in July 2010. These sections are currently being monitored (instrumentation, field surveys, other field testing).

**Instrumented UCPRC HVS test sections.** The HVS test pavements were constructed in May 2010 and loaded with the HVS equipment. The instrumented test cells can be used for future testing. Data was collected from rutting and reflection cracking tests at UCPRC (including laboratory testing). HMA/JPCP full-scale fatigue cracking tests using the HVS were conducted to validate the MEPDG transverse cracking models and the results provided validation. Further testing may continue under other funding sources.

**CONCLUSIONS**

Based on the comprehensive results achieved from this SHRP 2 R21 study, the key characteristics of these composite pavements were determined as follows:

- Excellent surface characteristics from the thin, high-quality asphaltic or concrete top layers. These include low noise (especially for permeable mixtures), high friction, very good initial smoothness, minimal rutting, and reasonable durability over a 10-to-15-year period for asphaltic type surfaces and much more than 20 years for concrete surfaces.

- Ability to rapidly renew a thin surface course as it wears under traffic and weather (e.g., removal and replacement of asphaltic materials, diamond grinding, or retexturing of concrete materials).

- Long-life low fatigue damage structural design of the lower PCC layer (e.g., designed for minimal fatigue damage over a 40+ year period).

- Avoidance of certain distress types that occur regularly in conventional pavements but are rare or nonexistent in composite pavements. For example:
  - HMA/JPCP or HMA/CRCP rarely show top-down HMA or PCC longitudinal cracking in the wheel paths (thermal gradients are reduced, lowering top-down fatigue damage in PCC).
  - These composites rarely show any low-temperature transverse cracking (they are bonded to the PCC), and they show only minimal amounts of rutting due to the thin high-quality mixture and thin layer.
  - Transverse reflection from JPCP joints can be controlled by the saw-and-seal procedure.
  - Transverse reflection of CRCP cracks rarely occurs in the HMA/CRCP included in the database.
  - PCC/JPCP composite pavement has shown no longitudinal top-down cracking.
- PCC/JPCP composite has shown only small amounts of fatigue transverse cracking.
- The durability of the PCC/JPCP surface has led to very little polishing in the wheel paths, which sometimes occurs on conventional PCC.

- Improved life cycle costs over a long life span due to overall lower construction costs (e.g., increased recycling, local aggregates, cement substitution amounts) and future maintenance (e.g., sawing and sealing of HMA joints will reduce impact and maintenance of reflection cracks) and rehabilitation costs over time (e.g., no full-depth repairs of PCC slab due to reduction in fatigue damage).
- Improved sustainability practices through structural and materials design of the lower PCC layer in both types of pavements: increased use of recycled or alternative materials (RCA, RAP), increased use of more local and less expensive aggregates, and higher substitution rates for cementitious materials (higher fly ash or other supplementary cementitious material such as lime cements, and slag) contents.

REFERENCES


