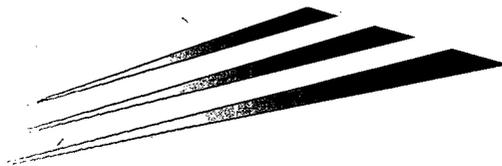


KENTUCKY TRANSPORTATION CENTER

College of Engineering

**EVALUATION AND ANALYSIS OF
HIGHWAY PAVEMENT DRAINAGE**



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Research Report
KTC-03-32/SPR207-00-1F

**EVALUATION AND ANALYSIS OF HIGHWAY
PAVEMENT DRAINAGE**

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In cooperation with

Transportation Cabinet
Commonwealth of Kentucky

And

The Federal Highway Administration
U.S. Department of Transportation

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EVALUATION AND ANALYSIS OF HIGHWAY PAVEMENT DRAINAGE

Executive Summary

This report presents an analysis of pavement drainage using various finite element models. The analysis included a range of pavement materials and drainage parameters. The computational tool in study was the SEEP/W option in the GEOSLOPE computer program. A steady-state saturated flow analysis was employed to generate flow paths and flux quantities through the cross-sectional area of the pavement. Finite element models in this study covered various drainage practices and quantified their relative drainage advantages. Finally, recommendations were provided for optimum drainage practices as well as future research topics in this area.

Keywords

Finite Element Analysis, Drainage Structures, Permeability, Water Infiltration, Pavement Design

Chapter 1.0 Introduction

1.1 Introduction

Pavement drainage plays an important role in the overall pavement performance. A variety of drainage practices have been developed throughout the years in order to promote pavement drainage. However, there is a need to quantify the effect of various drainage practices. Finite element modeling is an effective tool for characterization of various drainage practices. As with any finite element model, the accuracy of the model is a function of its input parameters. The input parameters for such models must be based upon laboratory measured and field verified data. In places where such data may not have been available, engineering judgment was exercised to generate reasonable ranges of drainage parameters verified by a number of sensitivity analyses. This approach allows future fine tuning and calibration of models presented in this report.

1.2 Objectives and Scope of Work

Researchers at Kentucky Transportation Center have been active in studying pavement drainage for over a decade. These studies have examined various pavement drainage features, such as edge drains, drainage blankets, etc., and their effectiveness. The objective of this study was to quantify the drainage characteristics of some key pavement construction practices in Kentucky. These practices have included the following scenarios: (1) a broken and seated (B&S) concrete layer covered with a Superpave asphalt layer; (2) the effect of a central collection pipe under pavement; (3) the effect of HMA surface permeability; (4) the effect of pavement geometry and pavement types; (5) the effect of cracks on pavement surface; (6) the effect of drainage blanket and its slope.

Chapter 2.0 Research Background

2.1. Pavement Drainage and Pavement Performance

Pavement surface drainage has long been recognized as an important factor in roadway design. Effective surface water drainage of highway pavements is essential to maintaining a desirable level of service and traffic safety. Poor surface drainage contributes to accidents resulted from hydroplaning and loss of visibility from splash and spray.

In addition to surface drainage, pavement must be designed to allow adequate subsurface drainage. Long-term accumulation of water inside the pavement reduces the strength of unbounded granular materials and subgrade soils, and causes pumping of fine materials with subsequent pavement rapid deterioration. When a pavement is saturated with water, heavy vehicle loads cause severe hydraulic shocks leading to pumping, disintegration of cement-treated bases, stripping of asphalt, and overstressing of weakened subgrade. Water is also responsible for a large number of non-load related distresses such as: D-cracking in concrete pavements, and accelerated aging and oxidation in asphalt pavements (Cedergren, 1988). Therefore, pavement drainage design should be at the forefront of pavement design and not an afterthought.

2.2 Pavement Drainage Design Issues

A growing number of state highway agencies have abandoned the concept of pavement sealing. This was the result years of experience which led to the thinking that water infiltration into the pavement structure cannot be effectively stopped. Therefore, it may be more cost effective to invest in a subsurface drainage system. Cedergren (1988) projects that pavement life can be extended up to three times if adequate subsurface drainage systems are installed and maintained. Forsyth et al. report a ratio of 2.4 to 1 for reduction of new crack formation in Portland cement concrete (PCC) pavement with drainage, compared with pavements without drainage. Forsyth et al. also reported at least a 33 percent increase in service life for asphalt pavements and a 50 percent increase for PCC pavements. Ray and Christory (1989) observed premature pavement distresses in an undrained pavement section in France, inferring a reduction in service life of nearly 70 percent as compared with a drained section.

The benefit of a functional subsurface pavement drainage system will vary depending on climate, subgrade soils, and the design of the overall pavement system. The subsurface drainage system design decision is made by systematically considering the influences of these factors. Design of subsurface drainage system consists of balancing permeability and structural stability. Important design components consist of the base material, a separating filter layer to prevent infiltration of subgrade fines into the base, and a collection and removal system (e.g. edge drains). The AASHTO Design Guide (1993) provides guidelines for including pavement drainage as a design consideration.

AASHTO pavement drainage factors account for a poor drainage condition by requiring a thicker pavement, and vice versa. It must be noted that this type of design consideration is only a rough estimate and further work is needed to fully quantify the influence of pavement drainage on overall pavement performance.

The design of subsurface drainage is closely related to surface drainage characteristics and geometric design. Consequently, these considerations need to be carefully coordinated while designing the pavement. The road profile at any location is dictated by considerations for surface runoff characteristics. The main concern of the subsurface designer is to have a desirable longitudinal grade and cross slope at any given point along the roadway to ensure positive drainage. A minimum cross slope of 2 percent is specified for cambered sections in the AASHTO Policy on Geometric Design of Highways and Streets to reduce the risk of hydroplaning. However, it is not always possible to meet the minimum slope requirements at all points along the roadway. In such situations, special drainage installations, such as transverse drains, may be required. Other aspects of surface drainage that affect surface drainage design are the locations of the curb, gutter, inlets, and storm drains in urban areas, which affect the positioning of edgedrain pipes, drainage trenches, and outlets (NCHRP, 1997).

2.3. Recent Pavement Drainage Studies

The following is a listing of key research studies related to pavement drainage:

- (1) Investigation of the Influence of Rainfall on Pavement Performance (Sarraf, 1987; Fwa, 1987; Tart, Jr, 2000)
- (2) Evaluation of the Effectiveness of Existing Drainage System (Fleckenstien and Allen, 1996; Hagen and Cochran, 1996; Wyatt et al., 2000; Stormont et al., 2001).
- (3) Determination of Drainage Coefficients of Various Drainage Materials (Randolph et al., 1996a; Randolph et al., 1996b; Lindly and Elsayed, 1995; Kolisoja, et al., 2002; Tandon and Picornell, 1998)
- (4) Investigation of Field Moisture Distribution and Its Influence on Modulus of various Pavement Layers (Thom and Brow, 1987; Houston et al., 1995; Kim et al., 1994; Janoo and Shepherd, 2000; Ksaibati et al. 2000).
- (5) Considerations in Pavement Drainage System Design and Construction (Mallela et al., 2000; Richardson, 2001; Birgisson and Roberson, 2000)
- (6) Statistical and Numerical Modeling of Pavement Drainage Systems (Liang and Lytton, 1989; Rainwater et al., 2001; Hassan and White, 2001).

In recent years, a significant amount of work has been done to use computational modeling for characterization of pavement drainage. For example, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) developed a pavement design method for use in seasonal frost areas. In this method, the variability in soil moisture content was not included in the infiltration models. The main emphasis was placed on the fluctuation of the ground water table and freeze/thaw.

The finite element methods was also used by Hassan and White in a comprehensive study of pavement subdrainage systems. In this study, material hydraulic properties were determined in laboratory tests. Pavement subdrainage system outflow were measured for several rainfall events. A finite element model was developed and calibrated using various test data.

Chapter 3.0 Pavement Drainage Criteria

To evaluate the effectiveness of the subsurface drainage system, there is a need to establish criteria to quantify the drainage performance. The following sections provide a summary of various pavement drainage criteria.

3.1 The Inflow-Outflow Concept

A steady-state flow in a saturated medium is often assumed for pavement drainage modeling purposes. For this to be accomplished, the outflow capabilities of the subgrade-pavement systems must be at equal to the inflow from all sources. The following model is typically used:

$$\sum O \geq \sum I$$

where $\sum I$ represents all inflow sources and $\sum O$ represents all outflow possibilities.

3.2 Flow Time Through Pavement Systems

In cold regions where freezing occurs to significant depths, proper drainage must be provided to effectively drain the pavement structure in the freeze zone. Calculations should be made to make certain that no water can remain in the pavement long enough to freeze. The water travel speed (v_s) through the drainage system can be estimated using the Darcy's law in the following format:

$$v_s = k i / n_e$$

Where the coefficient of permeability = k in the drainage layer, the effective porosity = n_e , and the slope in the direction flow = i . The water travel time then can be estimated using the following relationship for the drainage time over a distance = S in the pavement:

$$t = S / v_s$$

3.3 Drainage Time of a Rain Event

The rain water is not instantaneously drained through the pavement. The rain water (Q_p) has to infiltrate through various layers of a pavement before percolating into the subgrade soil. The time for 100 percent of the quantity of water to drain would be:

$$t_{100} = Q_p / q_s$$

where q_s is the unit seepage quantity, which is estimated by the equation $q = ki$, and t_{100} represents the time for 100 percent drainage of the quantity of water Q_p by downward seepage into the subgrade at a discharge rate of flow = q_s (Cedergren, 1974).

Chapter 4.0 FEM Analysis of Pavement Subsurface Drainage

In this study a series of finite element analyses were performed to characterize various drainage scenarios. These scenarios were designed to represent typical pavement subdrainage systems in Kentucky. The finite element models were designed to evaluate the following: (1) the effect of a broken and seated (B&S) concrete layer with or without a Superpave asphalt layer; (2) the effect of a central collection pipe; (3) the effect of Superpave HMA surface; (4) the effect of pavement geometry and pavement types; (5) the effect of cracks on pavement surface; (6) the effect of the slope of drainage blanket.

4.1 Analysis Approach

The subdrainage analyses were conducted using the SEEP/W routine of the GEOSLOPE computer program. SEEP/W is a 2-D finite element software product that can be used to model the movement and pore-water pressure distribution within porous materials such as soil and rock. It can model both saturated and unsaturated flow, a feature that greatly broadens the range of problems that can be analyzed. SEEP/W includes three executable programs: DEFINE, for defining the model, SOLVE for solving the problem, and CONTOUR for presenting the results in a graphical form.

The finite element models in this study were developed based upon a steady-state saturated flow assumption. The models were used to determine the flow paths and water flux quantities through the cross-sectional area of the pavement. These analyses were replicated to represent various geometries and layer conditions. The model solutions were then compared to determine the most efficient drainage scenario based upon the inflow-outflow ratio criteria.

When developing the finite element mesh, 8-node quadrilateral elements were used for each layer of the pavement. At the bottom of the soil, the infinite element was used. A constant water head of $H = 1$ ft was applied on the surface of the pavement. Around the collection pipes, a constant head of $H = 0$ ft was applied. It was also assumed that the side and bottom of the pavement were impermeable.

4.2 Effect of Superpave Overlay on Top of Broken and Seated PCCP

Old and distressed portland cement concrete pavements are often recycled through the process of breaking and seating. The broken and seated PCCP serves as a strong base layer in an overlay structure. The study was designed to evaluate the drainage properties of such a layer. The study included a Superpave hot mix asphalt overlay. The analysis was conducted with and without an asphalt overlay. The profile dimensions and layer components of each part were listed in Tables 1 and 2. The first section was modeled without a Superpave surface overlay. While the second section included an asphalt overlay: a two-layer Superpave surface which consisted of a 12.7mm (0.5 inch) layer and a 9.5mm (0.375 inch) layer. At each edge of these pavements, a trench with a collection pipe was placed for drainage purposes.

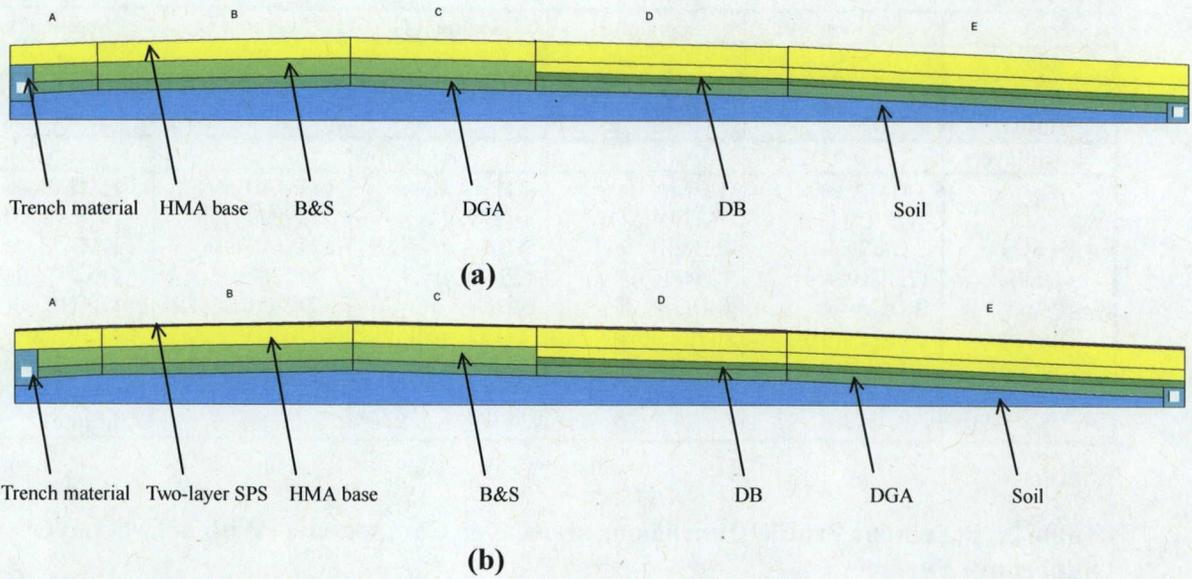


Figure 1. Pavement Profile Types: (a) without Superpave Surface, (b) with a Two-Layer Superpave Surface.



Figure 2. Finite Element Mesh and Boundary Conditions: Transverse Cross-Section of Pavement without Superpave Overlay.

Table 1. Pavement Profile Dimensions and Layer Components (No Superpave Surface)

| | Segment A | Segment B | Segment C | Segment D | Segment E |
|--|--|--|---|---|---|
| Slope | 4% | 2% | -2% | -2% | -4% |
| Length m(ft) | 1.2(4) | 3.6(11.8) | 2.7(8.7) | 3.6(11.8) | 5.5(18.2) |
| No. of layers | 4 | 4 | 4 | 5 | 5 |
| Layer Materials And Thickness mm(in) | 1 HMA Base (279.4(11)) 2 B&S (254(10)) 3 DGA (152.4(6)) 4 Soil (semi- infinite) | 1 HMA Base (279.4(11)) 2 B&S (254(10)) 3 DGA (152.4(6)) 4 Soil (semi- infinite) | 1 HMA Base (279.4(11)) 2 B&S (254(10)) 3 DGA (152.4(6)) 4 Soil semi- infinite) | 1 HMA Base (279.4(11)) 2 HMA Base (152.4(6)) 3 DB (101.6(4)) 4 DGA (152.4(6)) 5 Soil (semi- infinite) | 1 HMA Base (279.4(11)) 2 HMA Base (152.4(6)) 3 DB (101.6(4)) 4 DGA (152.4(6)) 5 Soil (semi- infinite) |

Table 2. Pavement Profile Dimensions and Layer Components (With a Two-Layer Superpave Surface)

| | Segment A | Segment B | Segment C | Segment D | Segment E |
|---|---|---|--|---|---|
| Slope | 4% | 2% | -2% | -2% | -4% |
| Length m(ft) | 1.2(4) | 3.6(11.8) | 2.7(8.7) | 3.6(11.8) | 5.5(18.2) |
| No. of layers | 6 | 6 | 6 | 7 | 7 |
| Layer Materials and Thickness mm(in) | 1 Superpave (12.7(0.5)) 2 Superpave (9.5(0.375)) 3 HMA Base (279.4(11)) 4 B&S (254(10)) 5 DGA (152.4(6)) 6 Soil (semi- infinite) | 1 Superpave (12.7(0.5)) 2 Superpave (9.5(0.375)) 3 HMA Base (279.4(11)) 4 B&S (254(10)) 5 DGA (152.4(6)) 6 Soil (semi- infinite) | 1 Superpave (12.7(0.5)) 2 Superpave (9.5(0.375)) 3 HMA Base (279.4(11)) 4 B&S (254(10)) 5 DGA (152.4(6)) 6 Soil semi- infinite) | 1 Superpave (12.7(0.5)) 2 Superpave (9.5(0.375)) 3 HMA Base (279.4(11)) 4 HMA Base (152.4(6)) 5 DB (101.6/4) 6 DGA (152.4(6)) 7 Soil (semi- infinite) | 1 Superpave (12.7(0.5)) 2 Superpave (9.5(0.375)) 3 HMA Base (279.4(11)) 4 HMA Base (152.4(6)) 5 DB (101.6/4) 6 DGA (152.4(6)) 7 Soil (semi- infinite) |

The objective of this portion of the study was to evaluate the effectiveness of a broken and seated (B&S) layer and the effect of a Superpave surface on pavement drainage. This analysis was conducted for the pavement both with and without a Superpave overlay surface. The permeability numbers used for the analysis were listed in Table 3. The solutions are shown in Table 4 and Figures 3 and 4.

Table 3. Permeability Data

| Material No | Layer | Permeability cm/s(ft/day) |
|-------------|----------------------------------|------------------------------|
| 1 | HMA Base ¹ | 0.005(14.2) |
| 2 | B&S ² | 1.76(5000) |
| 3 | DB ³ | 0.71(2000) |
| 4 | DGA ⁴ | 0.000035(0.1) |
| 5 | Trench Material | 0.71(2000) |
| 6 | Soil | 0.0000035(0.01) |
| 7 | 12.7mm(0.375in) SPS ⁵ | 0.001(2.83) |
| 8 | 9.5mm(0.5in) SPS ⁶ | 0.002(5.67) |

Table 4. Total Flux Comparisons (per unit area)

| Distance from left end m(in) | Flux in Pavement without Superpave Surface (cm/s) | Flux in Pavement with Superpave Surface (cm/s) | Flux Difference between the two Pavements (cm/s) | Percentage of Change |
|------------------------------------|--|---|---|-------------------------|
| 0.25(10) | 0.0780 | 0.0666 | -0.0114 | -14.631% |
| 1.02(40) | 0.0658 | 0.0570 | -0.0088 | -13.439% |
| 2.03(80) | 0.0522 | 0.0460 | -0.0063 | -11.999% |
| 3.56(140) | 0.0366 | 0.0327 | -0.0039 | -10.649% |
| 4.83(190) | 0.0256 | 0.0227 | -0.0029 | -11.401% |
| 6.35(250) | 0.0150 | 0.0144 | -0.0006 | -3.93% |
| 8.13(320) | 0.0058 | 0.0058 | 0.0000 | 0.0857% |
| 10.16(400) | 0.0009 | 0.0014 | 0.0004 | 47.3454% |
| 12.20(480) | 0.0034 | 0.0030 | -0.0004 | -10.401% |
| 14.22(560) | 0.0102 | 0.0097 | -0.0005 | -4.491% |
| 15.75(620) | 0.0200 | 0.0178 | -0.0022 | -11.083% |
| 16.51(650) | 0.0272 | 0.0236 | -0.0036 | -13.324% |
| Total | 0.3408 | 0.3006 | -0.0401 | -11.78% |

Figure 3 shows the flow paths and velocity of the infiltration water. For both scenarios presented in Figure 3, most of water goes through the broken and seated concrete, which indicates that the B&S layer works as an efficient drainage layer.

Table 4 and Figure 4 show the flow quantity through the areas at various distances from the left end of the pavement. From the analysis results we can see that the Superpave surfaces decreased the total flux that infiltrated into the pavement. Figure 4 shows that

¹ HMA = Hot Mixed Asphalt Concrete;

² B&S = Broken Concrete and Sealant;

³ DB = Drainage Blanket

⁴ DGA = Dense Graded Aggregate

⁵ 9.5mm(0.375in) SPS = 9.5mm (0.375 in.) Superpave Asphalt Surface

⁶ 12.7mm(0.5in) SPS = 12.7mm (0.5 in.) Superpave Asphalt Surface

although the flux was reduced in a broken and seated PCCP as a result of the Superpave overlay, this reduction was not significant, perhaps due to high permeability of Superpave mixtures.

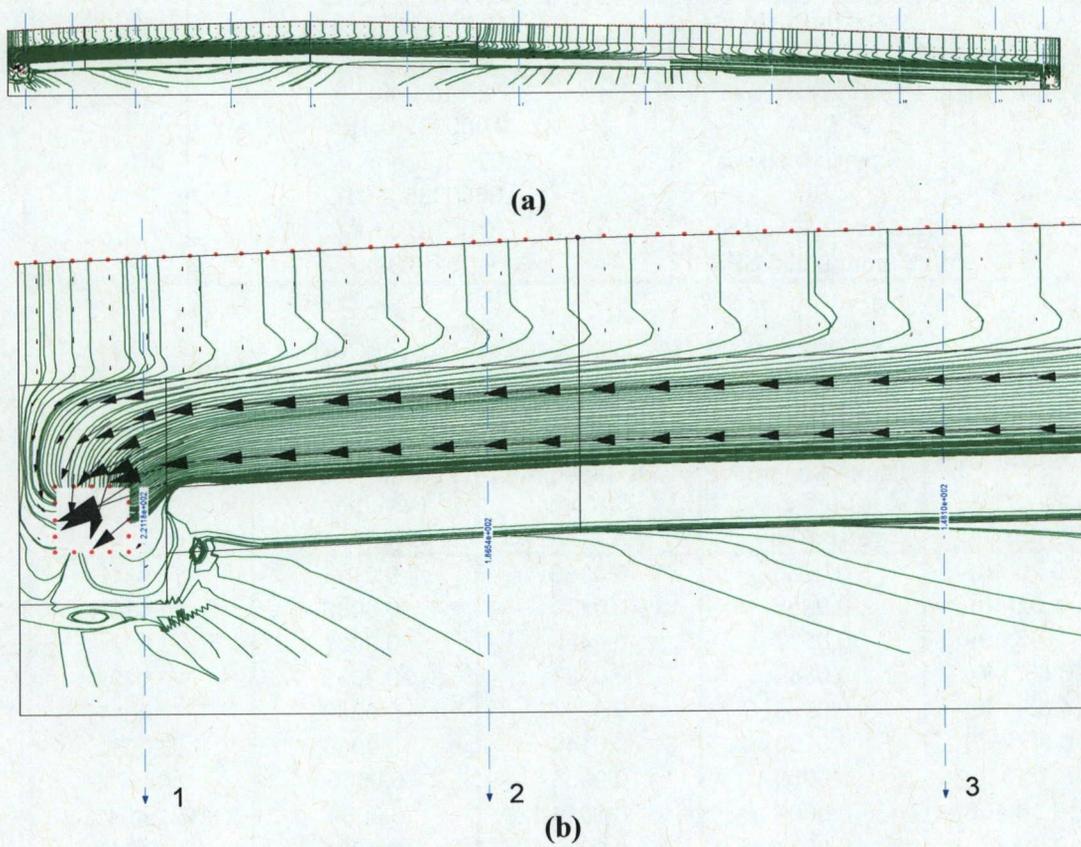


Figure 3. Water Flow Path and Velocity Vector. (a) Overall Transverse Pavement Cross-Section. (b) Transverse Cross-Section of the Pavement without Asphalt Surface, Plus a Left Drainage Pipe.

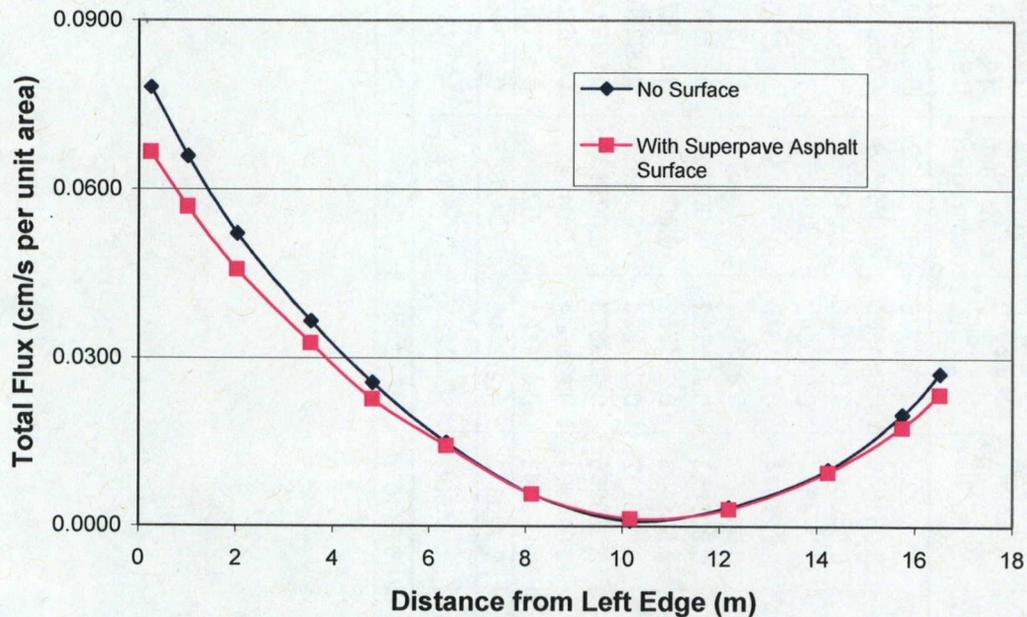


Figure 4. Total Transverse Flux for B&S-PCCP with and without a Superpave Overlay.

4.3 The Effect of Material Permeability

To investigate the effect of material permeability on pavement drainage, a series of analyses were conducted for the pavement with Superpave surfaces. This sensitivity analysis included three nominal permeability levels for each pavement material to represent various scenarios as shown in Table 6. The mid-range permeability was the value reported by the AASHTO (1992). The analysis results are listed in Table 7 and are shown in Figures 5 to 8.

Table 5. Material Permeability Used for Sensitivity Analysis

| LAYER | High Permeability cm/s(ft/day) | Mid-Range Permeability cm/s(ft/day) | Low Permeability cm/s(ft/day) |
|--------------------|-----------------------------------|--|----------------------------------|
| HMA Base | 0.035(99.2) | 0.005(14.2) | 0.001(2.83) |
| B&S | -- | 1.76(5000) | -- |
| DB | -- | 0.71(2000) | -- |
| DGA | 0.00212(6) | 3.5e5(0.1) | 1.4e5(0.04) |
| Trench Material | -- | 0.71(2000) | -- |
| Soil | -- | 3.5e6(0.01) | -- |
| 9.5mm(0.375in) SPS | 0.008(22.7) | 0.001(2.83) | 0.00044(1.25) |
| 12.7mm(0.5in) SPS | 0.04(113) | 0.002(5.67) | 0.00054(1.53) |

Table 6. Calculated Flux Data (cm/s per unit area)

| Distance from left m(in) | Mid-Range DGA Permeability | High DGA Permeability | Low DGA Permeability | Mid-Range HMA Base Permeability | Low HMA Base Permeability | High Perm. 9.5mm (0.375in) SPS | Low Perm. of 9.5mm (0.375in) SPS | High Perm. of 12.7mm (0.5in) SPS ⁷ | Low Perm. of 12.7mm (0.5in) SPS |
|-------------------------------|----------------------------------|--------------------------|-------------------------|---------------------------------------|---------------------------------|---|---|---|---------------------------------------|
| 0.25(10) | 0.066653 | 0.066678 | 0.066653 | 0.120422 | 0.024619 | 0.07222 | 0.060275 | 0.070032 | 0.058414 |
| 1.02(40) | 0.056999 | 0.057024 | 0.056999 | 0.094473 | 0.022088 | 0.061348 | 0.051965 | 0.059668 | 0.050514 |
| 2.03(80) | 0.046006 | 0.046028 | 0.046006 | 0.068277 | 0.018953 | 0.049088 | 0.042392 | 0.048086 | 0.041294 |
| 3.56(140) | 0.032758 | 0.032777 | 0.032758 | 0.041389 | 0.014679 | 0.034674 | 0.030542 | 0.034073 | 0.029917 |
| 4.83(190) | 0.022715 | 0.02273 | 0.022715 | 0.024742 | 0.011017 | 0.024044 | 0.021349 | 0.023454 | 0.021135 |
| 6.35(250) | 0.014395 | 0.014399 | 0.014388 | 0.014551 | 0.007393 | 0.014771 | 0.013901 | 0.014577 | 0.013785 |
| 8.13(320) | 0.005771 | 0.005773 | 0.005771 | 0.004357 | 0.003541 | 0.005823 | 0.005762 | 0.00572 | 0.005793 |
| 10.16(400) | 0.001378 | 0.001375 | 0.001378 | 0.000964 | 0.000904 | 0.001163 | 0.001552 | 0.001255 | 0.001578 |
| 12.20(480) | 0.003049 | 0.003065 | 0.003049 | 0.002441 | 0.0018 | 0.003212 | 0.002899 | 0.003067 | 0.002881 |
| 14.22(560) | 0.009714 | 0.00975 | 0.009714 | 0.011606 | 0.004857 | 0.009966 | 0.009378 | 0.009831 | 0.009311 |
| 15.75(620) | 0.017774 | 0.017819 | 0.017774 | 0.028771 | 0.007577 | 0.018861 | 0.016664 | 0.01841 | 0.016399 |
| 16.51(650) | 0.023618 | 0.023665 | 0.023617 | 0.045586 | 0.009084 | 0.025343 | 0.021821 | 0.02469 | 0.021387 |
| Total | 0.300833 | 0.301083 | 0.300822 | 0.45758 | 0.126512 | 0.320513 | 0.278499 | 0.312863 | 0.272407 |
| Difference from Mid- range | | 0.00025 | -1E-05 | 0.156747 | -0.17432 | 0.01968 | -0.02233 | 0.012031 | -0.02843 |
| Percent of Difference | | 0.0832% | -0.0035% | 52.1045% | -57.946% | 6.5418% | -7.424% | 3.9991% | -9.449% |

⁷ SPS=Superpave Surface

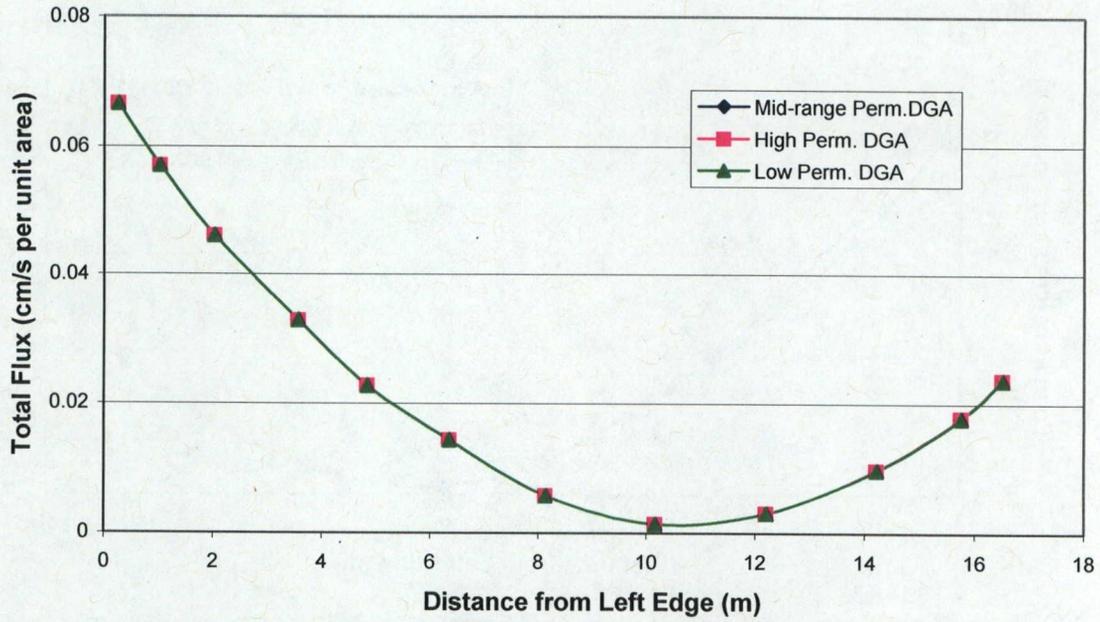


Figure 5. Effect of Permeability of DGA on Total Flux

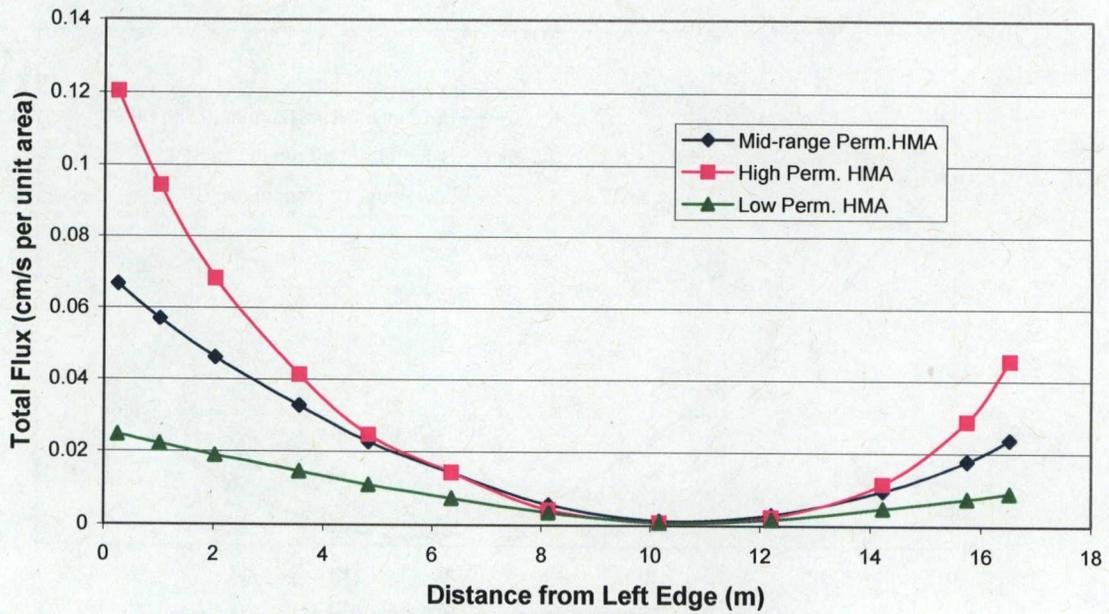


Figure 6. Effect of Permeability of HMA Base on Total Flux in the Pavement

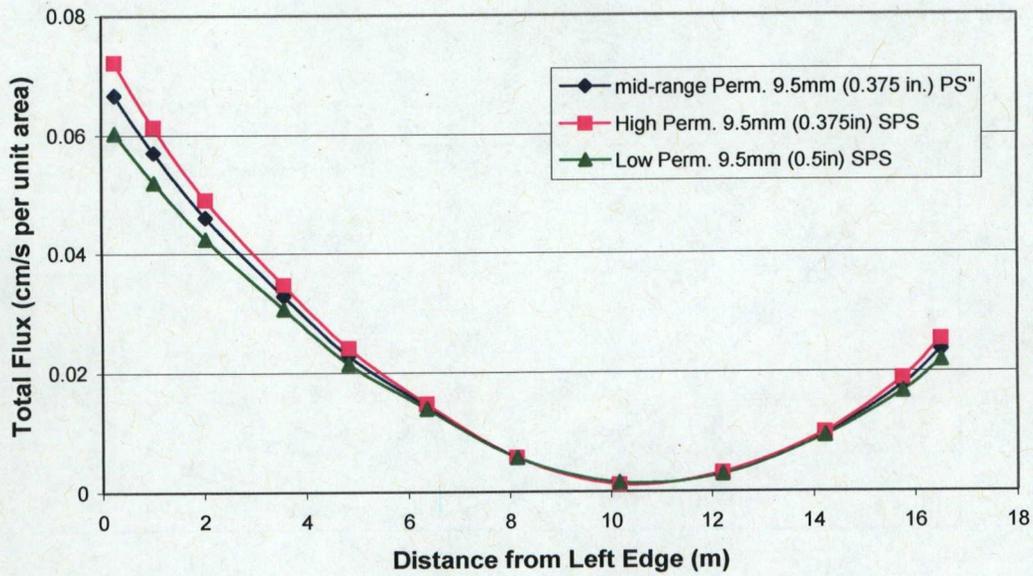


Figure 7. Effect of Permeability of 9.5mm (0.375in.) Superpave Surface on Total Flux in the Pavement.

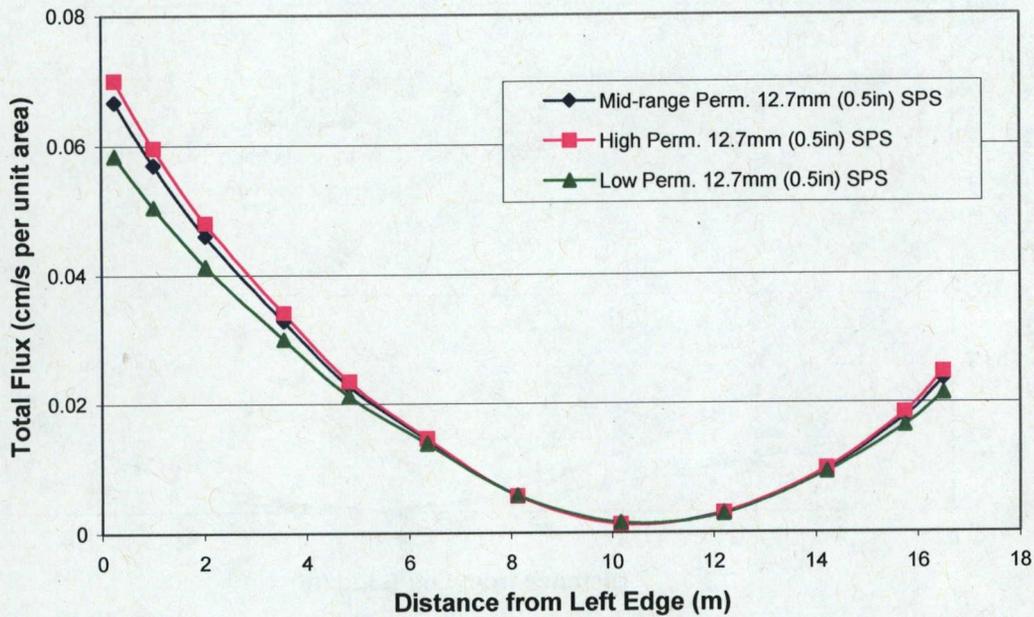


Figure 8. Effect of Permeability of 12.7mm (0.5in.) Superpave Surface on Total Flux in the Pavement

The analysis showed that the permeability of DGA had little effect on the pavement drainage. The permeability of AC base had a significant effect on the pavement drainage.

The permeability of all Superpave surfaces had a moderate effect on the pavement drainage.

4.4 Effects of Central Longitudinal Pipe

An edgedrain generally consists of a pipe in a trench filled with a geotextile-wrapped aggregate. The function of edgedrain is to collect the free water infiltrated into the base and subgrade to an outlet. It is important to note that often a center drain is added to facilitate pavement. The location of the central pipe is shown in Figure 9, and the FEM analysis results are illustrated by Figures 10 to 12 and Table 7.

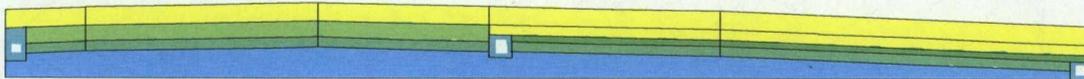


Figure 9. Location of Central Longitudinal Pipe

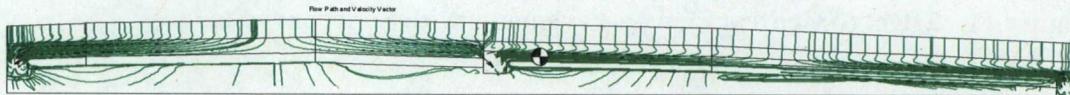


Figure 10. Water Flow Paths for Pavement with Central Longitudinal Pipe

Table 7. Calculated Flux Data with Central Longitudinal Pipe (cm/s per unit area)

| Flux Line No. | Distance from Left Edge(in) | Without Superpave Surface, and With Central Pipe | With Superpave Surface, and With Central Pipe |
|---------------|-----------------------------|--|---|
| 2 | 10 | 145.56 | 117.36 |
| 3 | 40 | 109.23 | 88.77 |
| 4 | 80 | 65.676 | 53.92 |
| 5 | 140 | 7.673 | 6.355 |
| 6 | 190 | 43.055 | 35.53 |
| 7 | 250 | 106.75 | 86.8 |
| 8 | 320 | 61.256 | 56.22 |
| 9 | 400 | 22.915 | 21.76 |
| 10 | 480 | 0.6087 | 0.6953 |
| 11 | 560 | 24.335 | 23.24 |
| 12 | 620 | 53.453 | 49.02 |
| 13 | 650 | 74.177 | 66.70 |

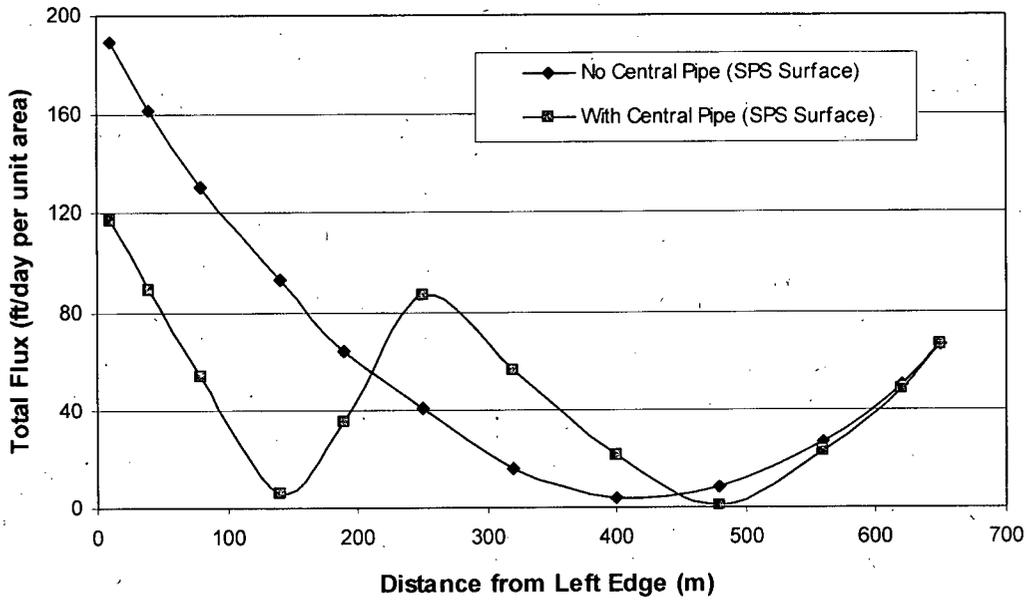


Figure 11. Effect of Central Pipe on Pavements with Superpave Surface

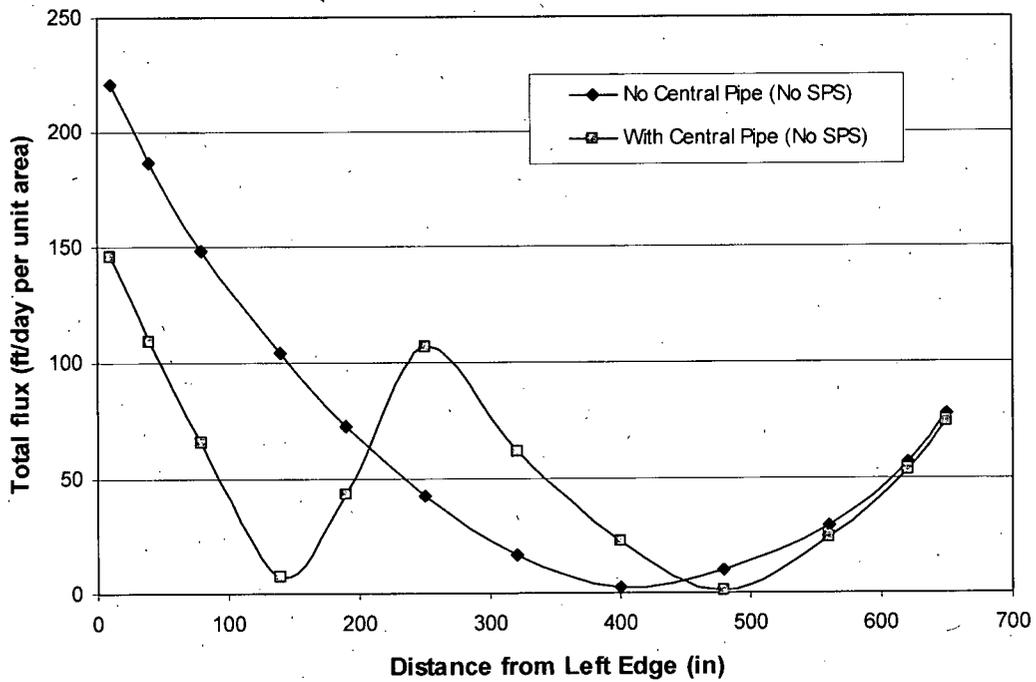
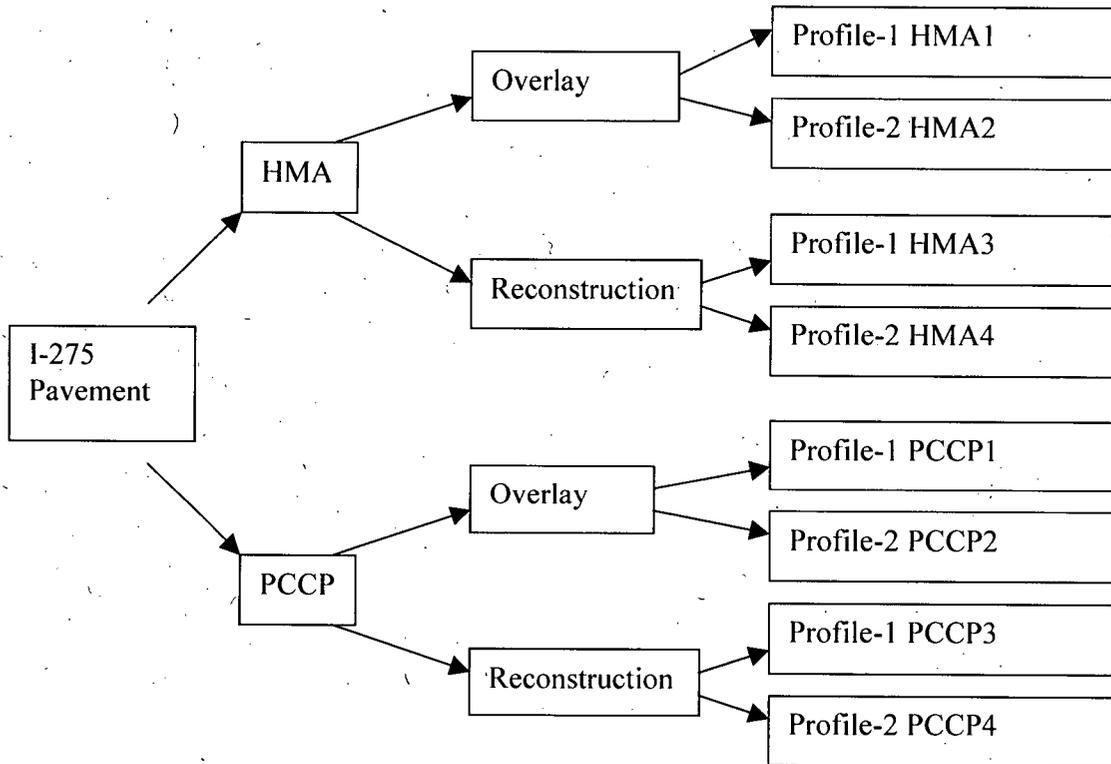


Figure 12. Effect of Central Pipe on Pavements without Superpave Surface

From Table 3 and Figures 10 to 12, one can see that the central drain pipe caused a change in the pavement drainage characteristics. The central pipe contributes to more efficient drainage of the pavement.

4.5 Effect of Geometry and Pavement Type

The objective of this analysis was to evaluate the effect of pavement geometry and pavement type (flexible or rigid) on pavement drainage. This analysis is performed by comparing the drainage ability of the pavement rehabilitation alternatives which have been proposed for I-275 freeway in Kentucky. There were eight alternatives that were considered for this rehabilitation, which are list in the following flow chart.



Where: HMA=Hot mixed asphalt pavement
 PCCP=Portland cement concrete pavement
 Overlay=the existing pavement will not be removed but overlaid with new layers
 Reconstruction=the existing pavement will be removed

In the following analysis, the alternatives were presented as HMA1 through 4 and PCCP 1 through 4. There were two options for the cross-section profile of the pavement, which were shown in the sketches of the pavement structure. The difference between Profile-1 and Profile-2 is the slope of left shoulder and the slope of left lane.

HMA1 and HMA2 have six layers: 1.5-inch HMA surface, 3.5-inch HMA base, two 4-inch HMA base lifts, existing 11-inch concrete pavement, and existing 6-inch DGA.

HMA3 and HMA4 have six layers: 1.5-inch HMA surface, 4.5-inch HMA base, two 5.5-inch HMA base lifts, 4-inch drainage blanket, and 4-inch DGA.

PCC1 and PCC2 have four layers: 10-inch concrete pavement, 1-inch drainage blanket, 11-inch existing concrete pavement, and 6-inch existing DGA.

PCC3 and PCC4 have three layers: 13-inch concrete pavement, 4-inch drainage blanket, and 4-inch DGA.

A 2-D steady-state analysis was conducted by using SEEP/W software for each alternative. The material permeability used is listed in Table 9.

Table 8. Material Permeability for Pavement of I-275 Highway in Kentucky

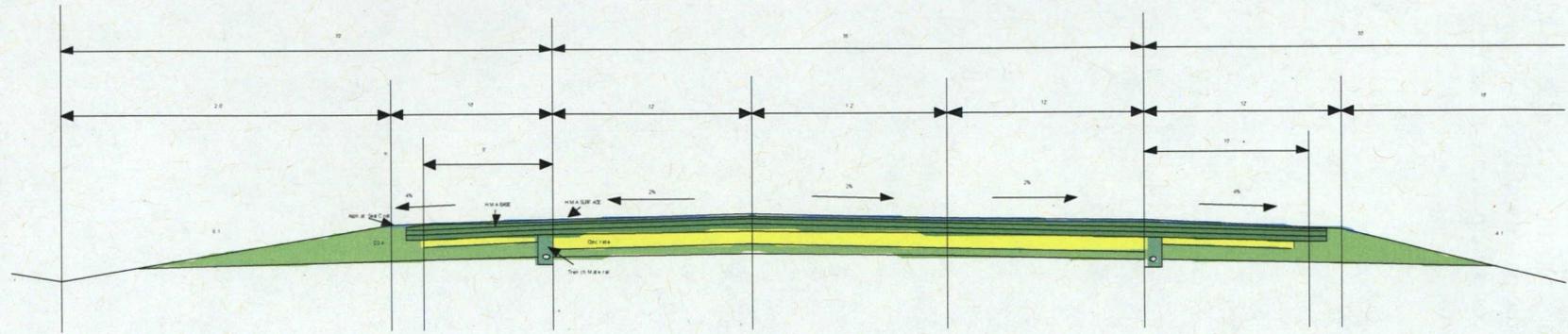
| Material | Permeability (ft/day) |
|-------------------|-----------------------|
| Concrete | 6.0E-7 |
| HMA surface | 6.6 |
| HMA base | 28.7 |
| Drainage blanket | 2000 |
| Trench material | 2000 |
| DGA | 0.1 |
| Asphalt seal coat | 0.07 |

For each analysis, a water head of 0.5-ft was applied on the pavement surface, and the water head was assumed to be zero at the collection pipe. The analysis results are listed in Table 10 and shown in Figures 14 through 17.

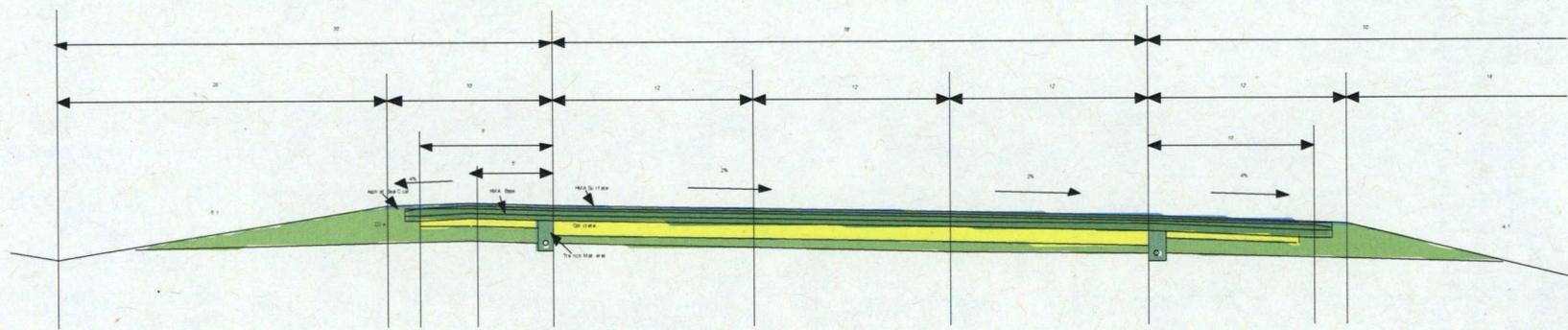
Comparing the flux distribution of HMA1 and HMA2 (Figure 14) one can see that more water percolates into the pavement through the driving lanes in HMA2. On the other hand, HMA3 and HMA4 (Figure 15) have very similar drainage performances.

For the concrete pavement, most of the water goes into pavement through the DGA outside the concrete shoulder. Comparing the PCC1 and PCC2 (Figure 16) one can observe that less water goes into the driving lanes under the PCCP2 scenario. Furthermore, the PCCP2 type of pavement showed improved drainage when a drainage blanket as added. When comparing the PCCP3 and PCCP4 (Figure 17), it was demonstrated that these two scenarios have very similar drainage behaviors.

The analysis results showed that pavement geometry parameters that were selected did not have a significant effect on subsurface drainage, but the pavement type does have a significant effect on pavement drainage. For example, a concrete pavement can prevent water infiltration more effectively than an asphalt pavement.

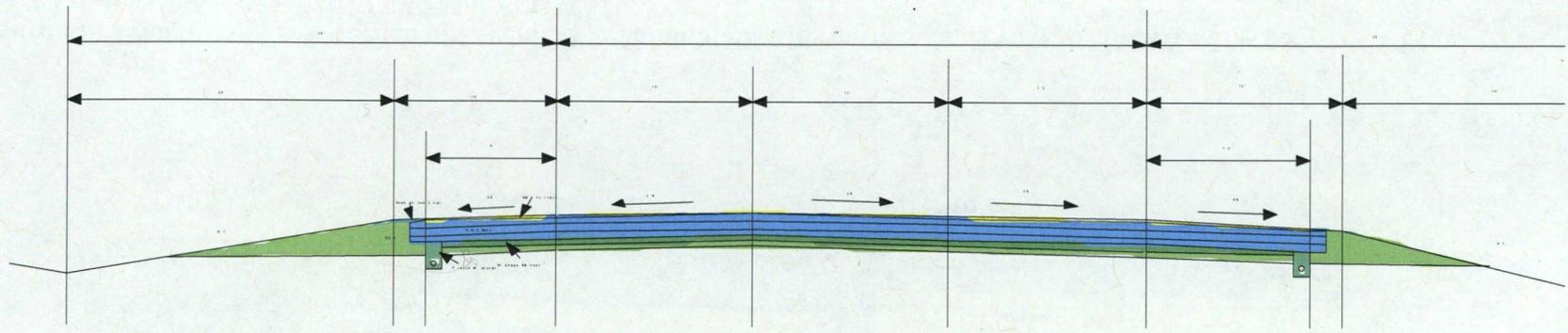


(a)

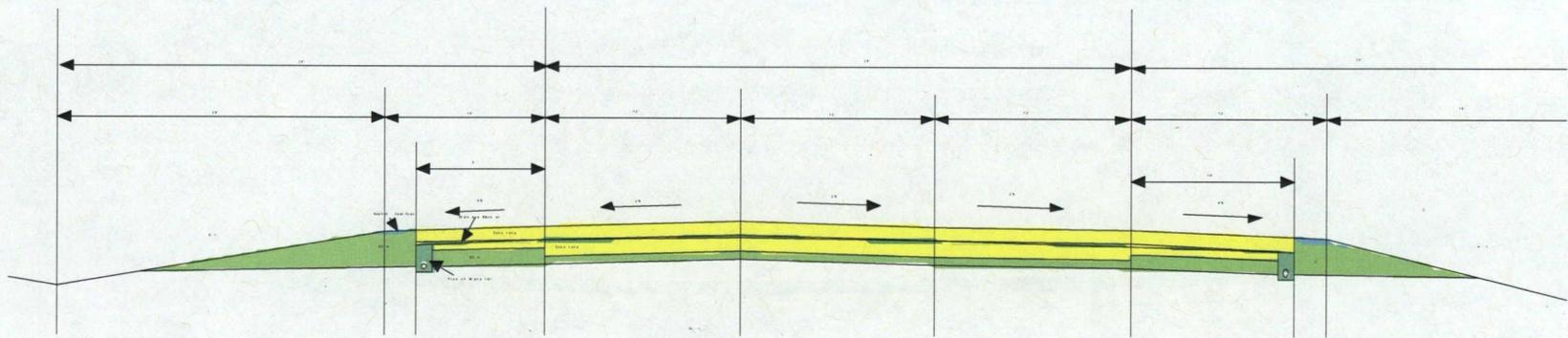


(b)

Figure 13. Transverse Cross-section of Pavement Rehabilitation Alternatives. (a. HMA1, b.HMA2, c HMA3, d. PCCP1, e. PCCP3, f. Detail Construction of Left Side of HMA1)



(c)



(d)

Figure 13. Transverse Cross-section of Pavement Rehabilitation Alternatives. (a. HMA1, b.HMA2, c HMA3, d. PCCP1, e. PCCP3, f. Detail Construction of Left Side of HMA1)

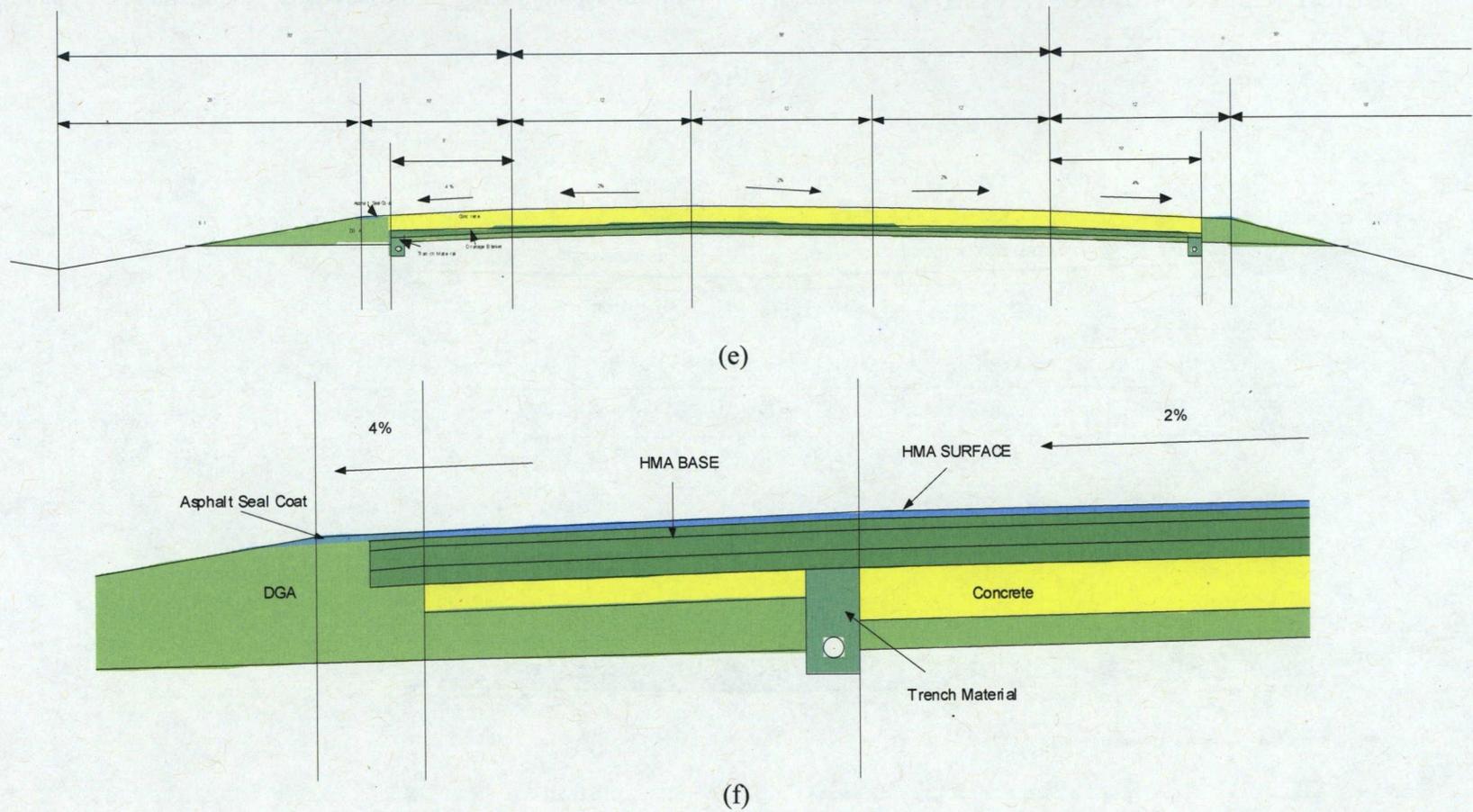


Figure 13. Transverse Cross-section of Pavement Rehabilitation Alternatives. (a. HMA1, b.HMA2, c HMA3, d. PCCP1, e. PCCP3, f. Detail Construction of Left Side of HMA1)

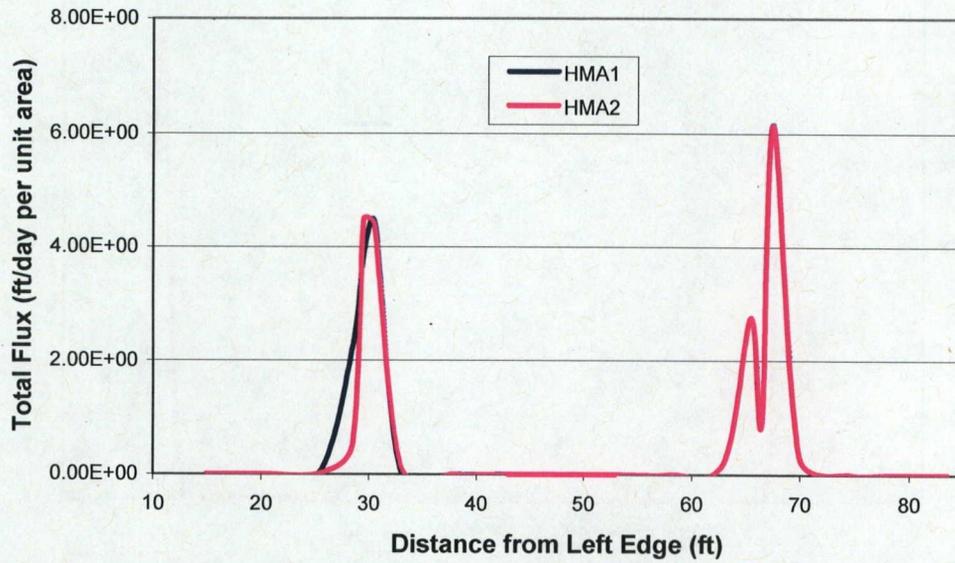


Figure 14. Flux Distribution along Pavement Transverse Cross-Section of HMA1 & HMA2.

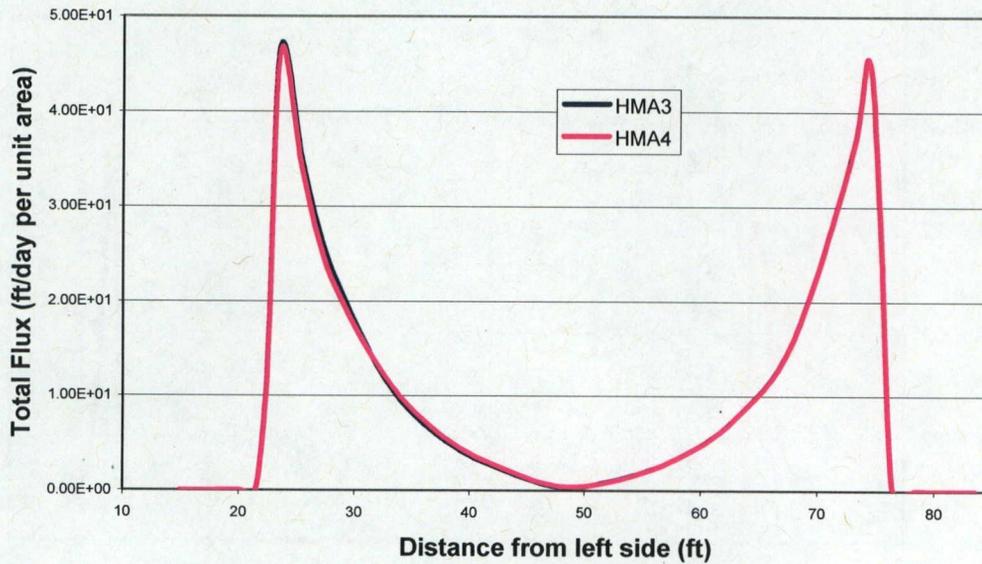


Figure 15. Flux Distribution along Pavement Transverse Cross-Section of HMA3 & HMA4.

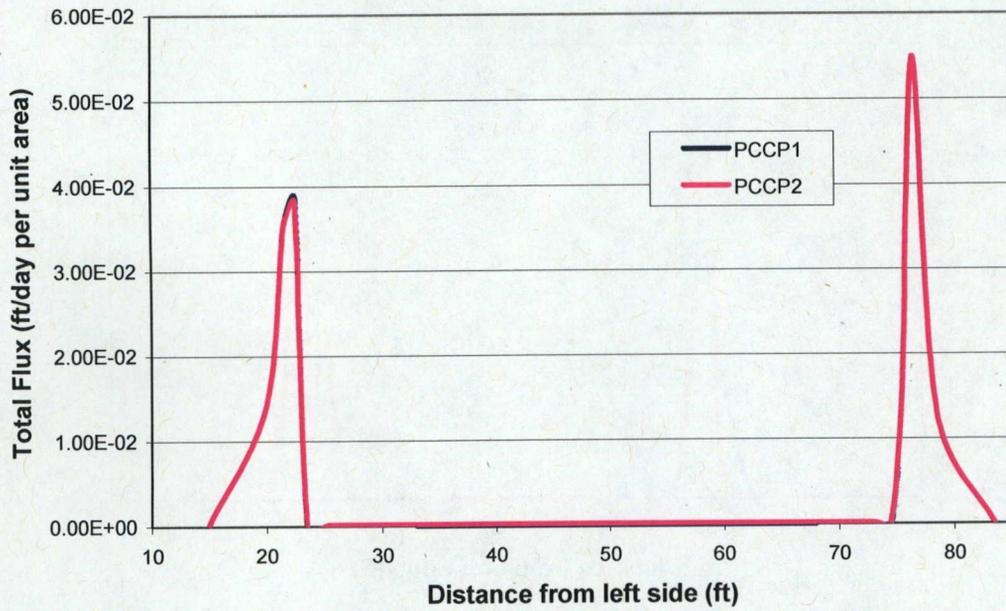


Figure 16. Flux Distribution along Pavement Transverse Cross-Section of PCC1 & PCC2.

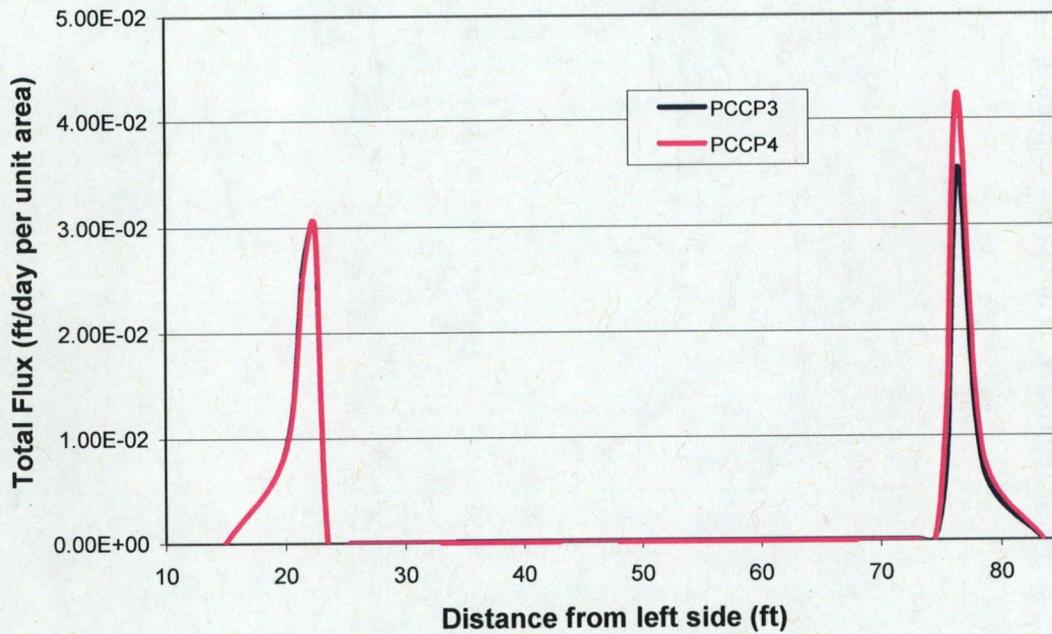


Figure 17. Flux Distribution along Pavement Transverse Cross-Section of PCC3 & PCC4.

4.6 Effects of Cracks and the Slope of Drainage Blanket

Saraf et al. (1987) studied the effect of rainfall on the performance of continuously reinforced concrete pavements (CRCP) in Texas. They reported that similar pavements located in different rainfall regimes performed initially the same. However, as various modes of distress, particularly cracks, were developed, pavement deteriorated at a more rapid rate. This investigation implied that the cracks and joints on pavement surface will increase the amount of water infiltration into pavement and cause rapid deterioration of performance.

To evaluate the effect of the cracks on pavement drainage performance, the finite element model of pavement alternatives for I-275 highway in Kentucky was modified by adding crack elements at various joints between the lanes. The widths of such cracks were set to be 1 cm (0.375 inch). The modification is shown in Figure 18 and the analysis results were presented in Figures 19 and 20. These analyses demonstrated that pavement drainage becomes a very serious issue when a pavement with poor drainage capability becomes heavily cracked.

To evaluate the effects of the slope of the subbase on pavement drainage, the layer construction of the HMA3 pavement alternative was modified as shown in Figure 23. The analysis results (Figure 20) imply that the increase of the slope of the drainage layer can increase the drainage ability of the pavement. But, this construction style needs to be accommodated with a thicker drainage blanket.

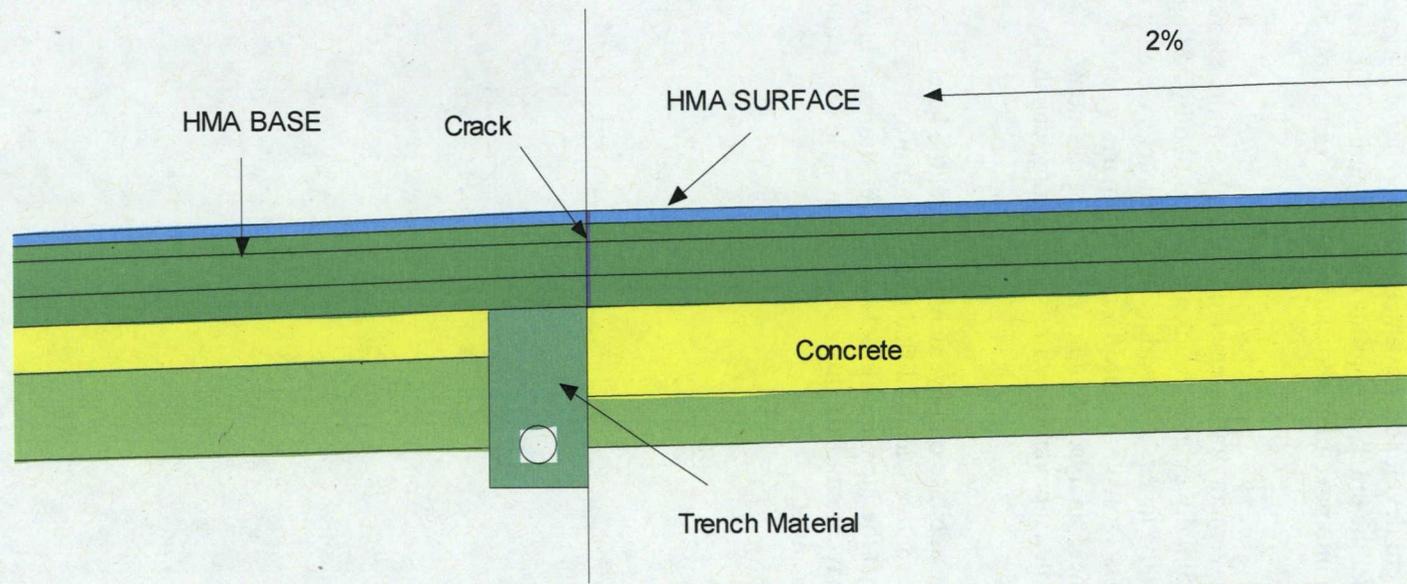


Figure 18. HMA1 Detail Pavement Construction with Permeable Joints between Lanes and between Lane and Shoulder (transverse, left side).

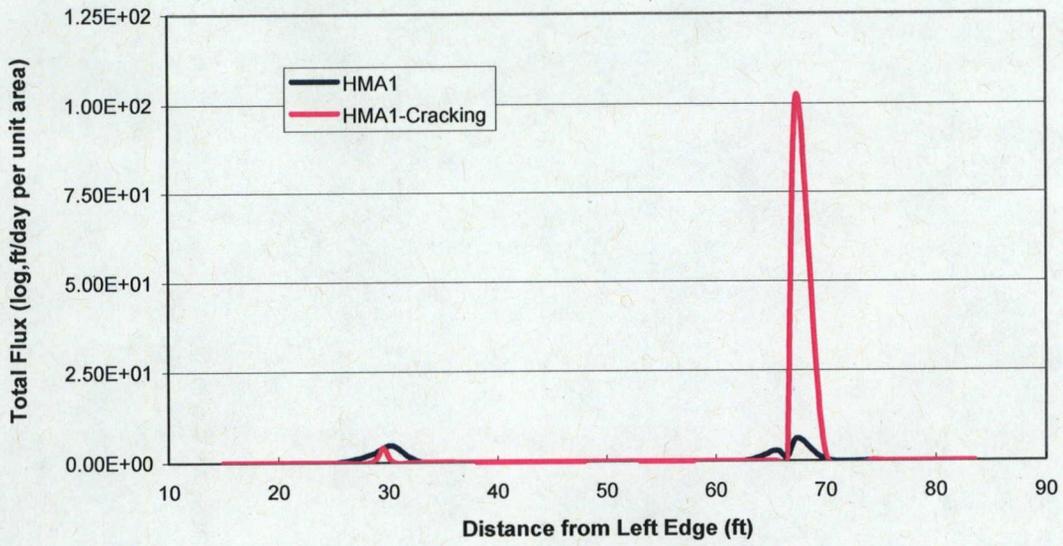


Figure 19. Flux Distribution Comparison between Cracked and Un-cracked HMA1 pavements.

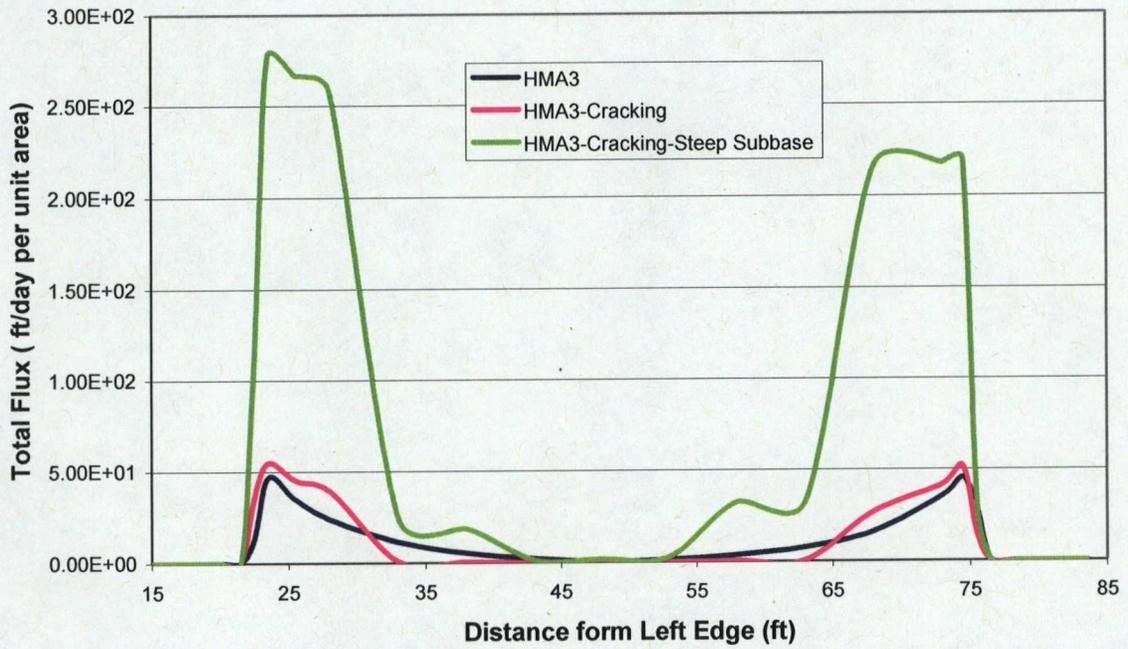


Figure 20. Flux Distribution Comparison between Cracked, Un-cracked HMA3 and HMA3 with Sloped Subbase Pavements.

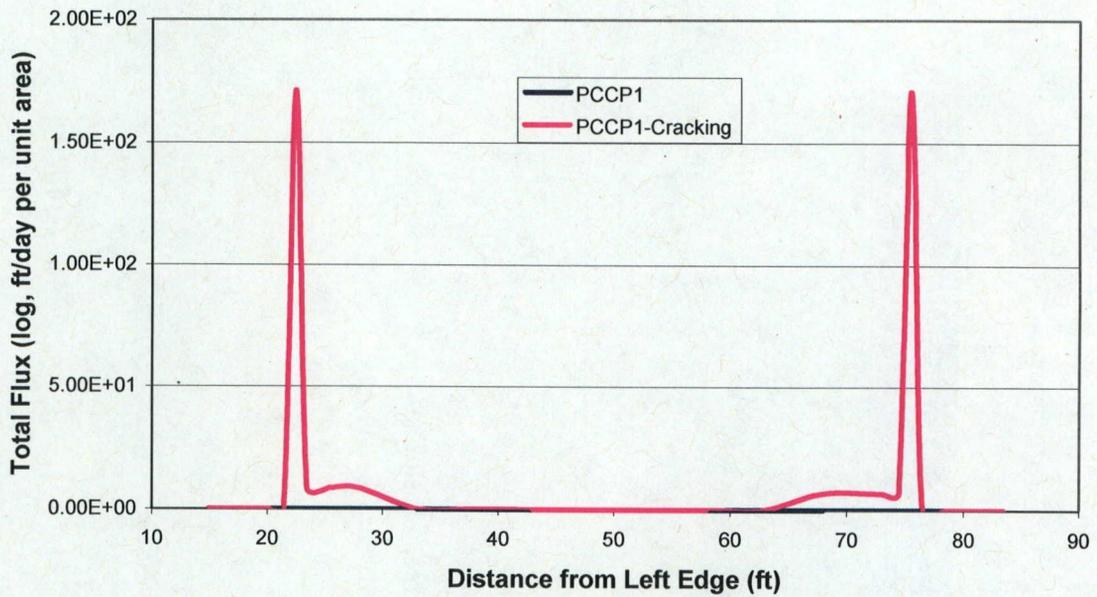


Figure 21. Flux Distribution Comparison between Cracked and Un-cracked PCCP1 Pavements.

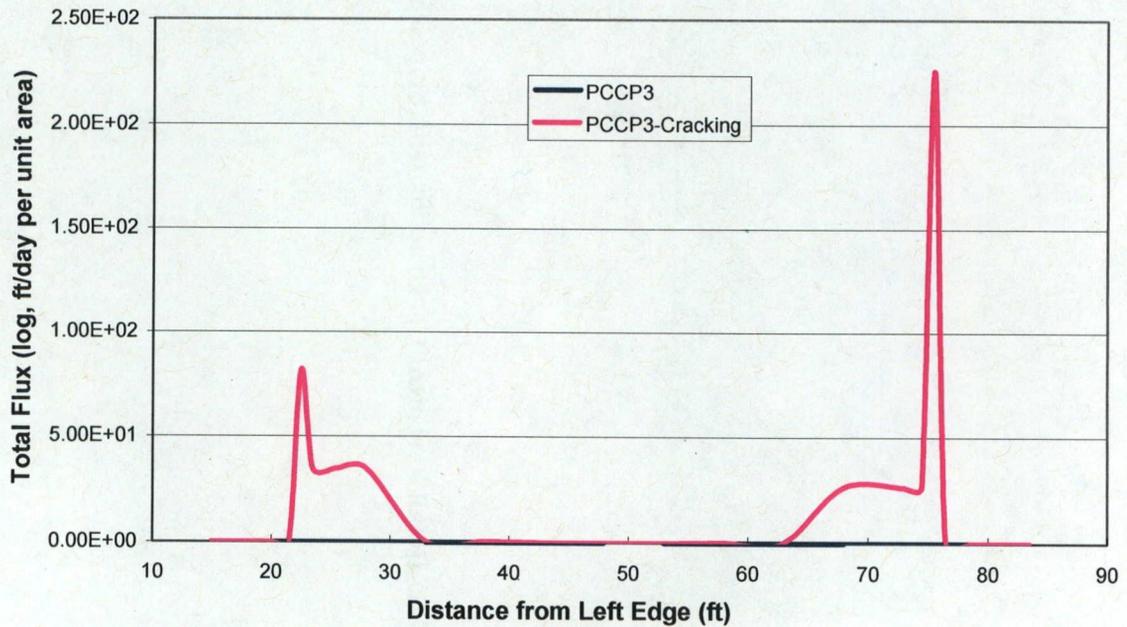


Figure 22. Flux Distribution Comparison between Cracked and Un-cracked PCCP3 Pavements.

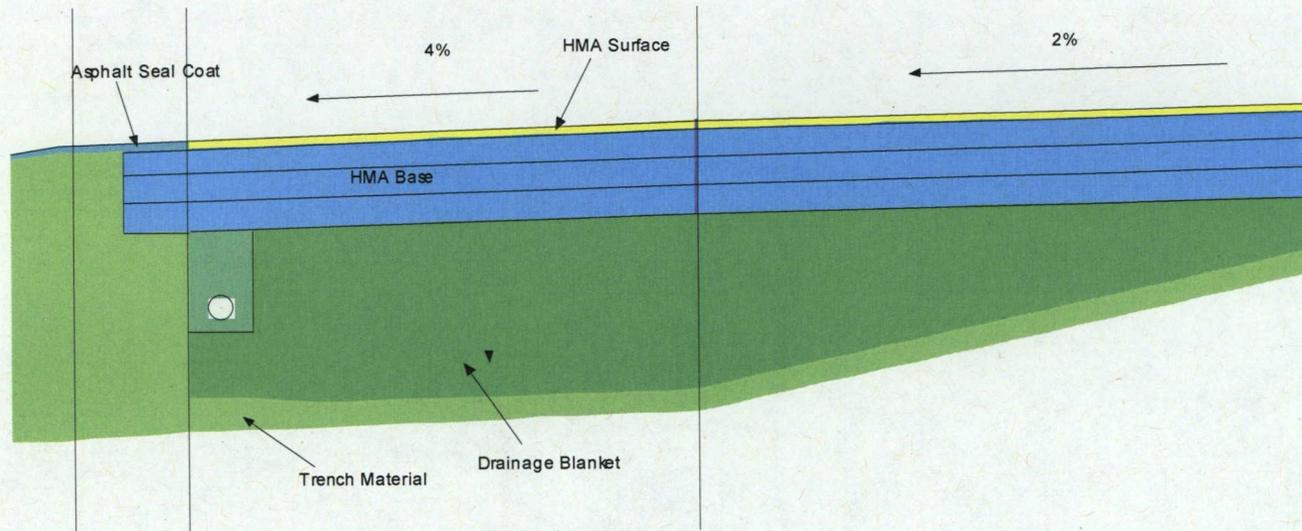


Figure 23. HMA3 Detail Pavement Construction with Sloped Subbase (transverse, left side).

Chapter 5.0 Conclusions and Recommendations

5.1 Conclusions

Various pavement drainage scenarios were modeled successfully using the finite element modeling techniques. These analyses led to the following conclusions:

- a) Broken and seated PCCP works as an effective drainage layer.
- b) Superpave surfaces reduced the water quantity that goes through the sides of the pavement significantly. But it had small effect on the water quantity that go through the center of the pavement.
- c) Superpave surfaces have higher permeability, and this must be handled through pavement subsurface drainage.
- d) A centrally located longitudinal drain can change the flux distribution in the pavement and therefore improve the drainage efficiency of the pavement.
- e) Pavement geometry parameters had little influence on subsurface drainage, but they do affect the surface drainage significantly.
- f) In the absence of cracks, flexible pavements offer a better drainage ability than concrete pavements.
- g) Both asphalt and concrete pavements need better drainage when they are cracked.
- h) The increase of the cross slope of the drainage blanket can increase the drainage ability of the pavement.

5.2 Recommendations

From the data in this study, the following recommendations are presented.

- All break-and-seat pavements should have positive drainage provided by longitudinal edge drains.
- On interstate widening projects, a longitudinal drain should be placed at the interface between the edge of the old concrete slab and the new asphalt drainage blanket or asphalt base. This will reduce the length of the flow path of the water and remove the water from the pavement structure more quickly.
- Stabilized drainage blankets with longitudinal edge drains should be provided on all new construction and major rehabilitations where pavement structure is added, with drainage blankets being used as part of the structural layers, if possible.
- To help alleviate the problems associated with Conclusion B above, it is recommended that superpave surfaces that have lower permeability be used to reduce the amount of water entering the pavement structure.
- It is recommended on new construction or on major rehabilitations where structure is added that each succeeding layer under the surface be designed with more permeability than the layer immediately above it. This will permit downward movement of the water that enters through the surface and will permit the surface water to reach the drainage blanket without hitting an impermeable layer.

- On new construction and major rehabilitations (where possible), it is recommended that the cross slope of the typical section be "steeper" than the longitudinal slope on all structural layers. This will help to prevent water from traveling longitudinally downgrade and force it to the side of the pavement where it will be intercepted by the longitudinal edge drain. The difference between the "steeper" cross slope of the lower layers and the two percent cross slope of the surface can be "made up" in the surface layer or the layer immediately under the surface.
- To prevent water from entering the pavement structure from below, a DGA layer would be very effective.

The 2-D steady-state analysis provides only a slice of what is actually happening in the pavement. It is recommended that this work be continued using a 3-D transient finite element tool. Additionally, the following topics are suggested for further research,

- Verify the drainage models by field data.
- Determine the relationship between pavement drainage and pavement performance.
- Develop a link to the upcoming NCHRP Project 1-37, *2002 Pavement Structural Design Guide*.

References

AASHTO (1993). Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials (AASHTO), 19993.

Birgisson, Bjorn and Ruth Roberson, (2000). Drainage of Pavement Base Material, *Transportation Research Record 1709*, TRB, National Research Council, Washington, D.C., 2000, pp11-18.

Cedergren, Harry R. (1974). Drainage of Highway and Airfield Pavements, John Wiley & Sons, Inc. New York.

Cedergren, Harry R. (1988). Why All Important Pavements Should Be Well Drained, *Transportation Research Record 1188*, TRB, National Research Council, Washington, D.C., 1988, pp56-62.

Fleckenstein, L. John and David Allen (1996). Evaluation of Pavement Edge Drains and Their Effect on Pavement Performance, *Transportation Research Record 1519*, TRB, National Research Council, Washington, D.C., 1996, pp28-35

Fwa, T.F. (1987); Water-Induced Distress in Flexible Pavement in a Wet Tropical Climate. *Transportation Research Record 1121*, TRB, National Research Council, Washington, D.C., 1987, pp57-65.

Hagen and Cochran, (1996); Comparison of Pavement Drainage Systems, *Transportation Research Record 1519*, TRB, National Research Council, Washington, D.C., 1996, pp1-10.

Hassan, Hossam F. and Thomas D. White (2001). Modeling Pavement Subsurface Systems, *Transportation Research Record 1772*, TRB, National Research Council, Washington, D.C., 2001, pp137-142.

Houston et al., (1995); Moisture and Strength Variability in Some Arizona Subgrades, *Transportation Research Record 1481*, TRB, National Research Council, Washington, D.C., 1995, pp35-43.

Janoo and Shepherd, 2000; Ksaibati et al. (2000). Effect of Moisture on Modulus Values of Base and Subgrade Materials, *Transportation Research Record 716*, TRB, National Research Council, Washington, D.C., 2000, pp20-29.

Kim, OK-Kee, et al. (1994). Electrical Resistance Tomography Imaging of Spatial Moisture Distribution in Pavement Sections, *Transportation Research Record 1435*, TRB, National Research Council, Washington, D.C., 1994, pp69-76.

- Kolisoja, et al., (2002); Laboratory Testing of Suction and Deformation Properties of Base Course Aggregates, *Transportation Research Record 1787*, TRB, National Research Council, Washington, D.C., 2002, pp83-89.
- Liang, Hui Shang and Robert L. Lytton, (1989); Rainfall Estimation for pavement Analysis and Design, *Transportation Research Record 1252*, TRB, National Research Council, Washington, D.C., 1989, pp42-49.
- Lindly, Jay K. and Ashraf S. Elsayed, (1995); Estimating Permeability of Asphalt-Treated Bases, *Transportation Research Record 1504*, TRB, National Research Council, Washington, D.C., 1995, pp103-111.
- Mallela, Jagannath, Leslie Titus-Glover, and Micheal I Darter (2000). Considerations for Providing Subsurface Drainage in Jointed Concrete Pavements, *Transportation Research Record 1709*, TRB, National Research Council, Washington, D.C., 2000, pp1-9.
- NCHRP Synthesis 239, (1997). Pavement Subsurface Drainage Systems (A Synthesis of Highway Practice), TRB, National Research Council, Washington, D.C..
- Rainwater et al., (2001); In Situ Measurement and Empirical Modeling of Base Infiltration in Highway Pavement Systems, *Transportation Research Record 1772*, TRB, National Research Council, Washington, D.C., 2001, pp143-150.
- Randolph et al., (1996a); In Situ Test for Hydraulic Conductivity of Drainage Bases, *Transportation Research Record 1519*, TRB, National Research Council, Washington, D.C., 1996, pp36-40.
- Randolph et al., 1996b; Laboratory Study of Hydraulic Conductivity for Coarse Aggregate Bases, *Transportation Research Record 1519*, TRB, National Research Council, Washington, D.C., 1996, pp19-27.
- Ray, M., and J.P. Christory (1989). Combating Concrete Pavement Slab Pumping: State-of-the-Art and Recommendations. Proceedings of 4th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, April 1989.
- Richardson, David N. (2001); AASHTO Drainage Coefficient for Flexible Pavements, *Transportation Research Record 1778*, TRB, National Research Council, Washington, D.C., 2001, pp73-80.
- Saraf, C. et al. (1987); Effect of Rainfall on the Performance of Continuously Reinforced Concrete Pavement in Texas, *Transportation Research Record 1121*, TRB, National Research Council, Washington, D.C., 1987, pp45-49.
- Stormont et al., (2001). Geocomposite Capillary Barrier Drain System with Fiberglass Transport Layers, *Transportation Research Record 1772*, TRB, National Research Council, Washington, D.C., 2001, pp131-136.

Tandon, Vivek, and Miguel Picornell, (1998). Proposed Evaluation of Base Materials for Drainability, *Transportation Research Record 1596*, TRB, National Research Council, Washington, D.C., 1998, pp62-69.

Tart, Jr., Rupter G. (2000). Pavement Distress and Roadway Damage Caused by Subsurface Moisture and Freezing Temperatures, *Transportation Research Record 1709*, TRB, National Research Council, Washington, D.C., 2000, pp91-97.

Thom N.H. and S.F. Brow, (1987); Effect of Moisture on the Structural Performance of a Crushed-Limestone Road Base, *Transportation Research Record 1121*, TRB, National Research Council, Washington, D.C., 1987, pp50-56.

Wyatt et al., (2000); Effectiveness Analysis of Subsurface Drainage Features Based on Design Adequacy, *Transportation Research Record 1709*, TRB, National Research Council, Washington, D.C., 2000, pp69-76.