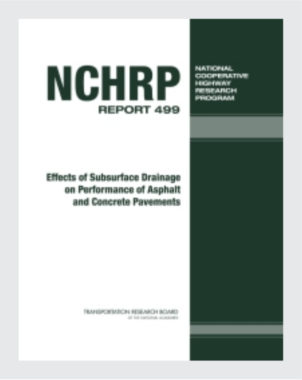

Effects of Subsurface Drainage on Performance of Asphalt and Concrete Pavements

DETAILS

0 pages | | PAPERBACK
ISBN 978-0-309-43125-5 | DOI 10.17226/21952

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 499

Effects of Subsurface Drainage on Performance of Asphalt and Concrete Pavements

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SUBJECT AREAS
Pavement Design, Management and Performance

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2003
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NCHRP REPORT 499

Project C1-34C FY'99

ISSN 0077-5614

ISBN 0-309-08758-9

Library of Congress Control Number 2003107410

Price $19.00

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

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Printed in the United States of America

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FOREWORD

By Edward T. Harrigan
Staff Officer
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This report presents the findings of a research project to evaluate the effects of subsurface drainage features on the performance of pavements through a comprehensive analysis of data available through June 2001 from the Long Term Pavement Performance experiments. The report will be of particular interest to engineers in the public and private sectors with responsibility for the design, construction, and rehabilitation of highway pavements.

NCHRP Project 1-34, "Performance of Subsurface Pavement Drainage," was completed in 1998. Its objective was to evaluate the effectiveness of subsurface pavement drainage systems for hot mix asphalt (HMA) and portland cement concrete (PCC) pavements, including permeable base and associated edgedrains, traditional dense-graded bases with and without edgedrains, and subsurface drainage features retrofitted on existing pavements

The findings of Project 1-34 were based on relatively small samples of HMA and PCC pavement sections with subsurface drainage features for which control sections were available for comparison. Pavement sections from the LTPP SPS-1 (flexible HMA pavement) and SPS-2 (rigid PCC pavement) experiments were not included because they were not of sufficient age at the time the project was underway.

Project 1-34B, "Effectiveness of Subsurface Drainage for HMA and PCC Pavements," was completed in 1999. It critically reviewed the results of Project 1-34 and developed an experimental plan to further test and evaluate Project 1-34's findings. Under NCHRP Project 1-34C, "Effects of Subsurface Drainage on Performance of Asphalt and Concrete Pavements," Dr. Kathleen Hall and her colleagues were asked to carry out this experimental plan with the objective of better quantifying the effects of subsurface drainage on pavement performance through an analysis of the SPS-1 and SPS-2 data.

The research team assembled the requisite material, structural, climatic, traffic, and performance data for the SPS-1 and SPS-2 experiments from LTPP data release 11.5 of 13 June 2001. (The as-constructed layer thickness and material-type data were updated in June 2002, using data extracted from release 12.0.) In addition, during the course of NCHRP Project 1-34C, the Federal Highway Administration, with NCHRP support, contracted for the video inspection of edgedrains at the SPS-1 and SPS-2 sites to physically determine their functionality. The results of these inspections were also used by the 1-34C research team in this study.

For the SPS-1 experiment, statistical analyses were conducted to determine whether or not the mean difference between undrained and drained test section pairs was significant for three HMA pavement performance indicators, viz., rutting, cracking, and International Roughness Index (IRI). In terms of IRI and cracking, the results of these analyses indicated that pavement sections with undrained dense-graded aggregate bases have tended to perform more poorly than sections of otherwise matching pavement designs with drained permeable asphalt-treated bases. However, sections with drained permeable asphalt-treated bases have tended to perform more poorly than sections of otherwise matching designs with undrained dense-graded asphalt-treated bases. In all cases, the results for rutting were so far inconclusive.

For the SPS-2 experiment, the same statistical analyses were conducted for three PCC pavement performance indicators, viz., IRI, transverse cracking, and longitudinal cracking. Here, pavement sections with undrained dense-graded aggregate bases have tended to perform more poorly than sections of otherwise matching pavement designs with drained permeable asphalt-treated bases. Similarly, pavement sections with undrained lean concrete bases have tended to perform more poorly than sections of otherwise matching designs with drained permeable asphalt-treated bases. No analyses were possible for faulting because the faulting levels were still so low that no consistent trends were apparent.

The final report includes a detailed description of the available data and the analysis procedures, a discussion of the research results and their limitations, a summary of the key findings, and two supporting appendixes:

- Appendix A: SPS-1 Details; and
- Appendix B: SPS-2 Details.

This published report includes the main text. Appendices A and B are available on request from NCHRP.

CONTENTS

CHAPTER 1

INTRODUCTION

PROBLEM STATEMENT

Subsurface drainage is commonly believed to be beneficial to the performance of both asphalt and concrete pavements. However, research to date has neither clearly demonstrated nor quantified the effects of subsurface drainage on asphalt and concrete pavement performance for different climates, soils, and traffic conditions. Past research on this topic has also failed to clarify whether nonfunctioning drainage (due to inadequate design, improper construction, or maintenance) results in pavements performing the same as, or worse than, pavements without any subdrainage installation at all. Without guidance on these matters, the practicing engineer faces a difficult task in judging whether or not subsurface drainage is a cost-effective pavement design component for a given project with a given set of climatic, soil, and traffic conditions.

RESEARCH OBJECTIVES

The SPS-1 experiment (Strategic Study of Structural Factors for Flexible Pavements) and SPS-2 experiment (Strategic Study of Structural Factors for Rigid Pavements) in the Long-Term Pavement Performance (LTPP) studies were designed to study, among other things, the effects of subsurface drainage on performance. The objectives of NCHRP Project 1-34C were to:

1. Assess the feasibility of using data available from the LTPP SPS-1 and SPS-2 experiments to evaluate the effects of subsurface drainage on the performance of asphalt and concrete pavements,
2. Recommend additional field data collection (e.g., inspection of subdrainage functioning) needed to complement the available SPS-1 and SPS-2 data in support of the first objective,
3. Develop a plan for analysis of SPS-1 and SPS-2 data for the purpose of quantifying the effects of subsurface drainage on the performance of asphalt and concrete pavements, and
4. Conduct a pilot analysis of the effects of subsurface drainage on performance of asphalt and concrete pavements in the SPS-1 and SPS-2 experiments, using the data available in the LTPP database and field inspection results.

RESEARCH APPROACH

This report presents the results of the assessment of the feasibility of using the SPS-1 and SPS-2 experiments to evaluate the effects of subsurface pavement drainage on pavement performance, and the results of the pilot analyses conducted. Based on these results, recommendations are given for additional field data collection and analysis work to be conducted in a subsequent study.

Most of the data used in this study were obtained from LTPP data release 11.5, dated 13 June 2001. The as-constructed layer thickness and material type data were updated in June 2002, using data extracted from release 12.0. Layer thickness and material type data for one site (Arkansas SPS-2) were obtained from the Southern LTPP Regional Center's Regional Information Management System (RIMS) database.

Although drainage is one of the main experimental design factors for both SPS-1 and SPS-2, inspection of the functioning of the drainage systems was not incorporated into the field monitoring program for these experiments. During the course of NCHRP Project 1-34C, the Federal Highway Administration, with NCHRP support, contracted for the video inspection of edgedrains for the SPS-1 and SPS-2 sites. The results of these inspections were used by the 1-34C research team in this study. However, as discussed later in this report, it is difficult to assess the functioning of the edgedrain systems definitively on the basis of video inspections alone.

ORGANIZATION OF THIS REPORT

The research conducted for NCHRP Project 1-34C is described in this report in the following sequence:

- Chapter 1—Introduction and research approach.
- Chapter 2—Effects of subsurface drainage on the performance of asphalt pavements in the LTPP SPS-1 experiment.
- Chapter 3—Effects of subsurface drainage on the performance of concrete pavements in the LTPP SPS-2 experiment.
- Chapter 4—Conclusions.
- Appendix A—Details of SPS-1 layouts, accumulated traffic, and video inspections.
- Appendix B—Details of SPS-2 layouts, accumulated traffic, and video inspections.

CHAPTER 2

EFFECTS OF SUBSURFACE DRAINAGE ON ASPHALT PAVEMENTS

DESCRIPTION OF LTPP EXPERIMENT SPS-1

The SPS-1 experiment (Strategic Study of Structural Factors for Flexible Pavements) was designed to assess the influence of the following factors on the performance of asphalt concrete pavements:

- Asphalt concrete thickness,
- Base type,
- Base thickness,
- Subdrainage,
- Climate,
- Subgrade, and
- Truck traffic level.

The Strategic Highway Research Program's original experimental design and research plan for SPS-1 are described in Reference 1. The design factorial for the SPS-1 experiment is shown in Table 1. The first two digits (01) of the number shown within each cell signify the SPS-1 experiment; the last two digits signify the test section number of each design. The base types listed in Table 1 are the following:

- AGG—dense-graded aggregate
- ATB—asphalt-treated base
- ATB/AGG—asphalt-treated base over dense-graded aggregate
- PATB/AGG—permeable asphalt-treated base over aggregate
- ATB/PATB—asphalt-treated base over permeable asphalt-treated base.

Other than some thickness deviations, the pavement structures actually constructed conform to the experiment design shown in Table 1, with one important exception: which sections are drained and which are not. The field inspection of the drains, discussed in more detail later in this chapter, found several instances of the following discrepancies:

- Some pavement sections were found to have drains installed even though they should not according to the experiment design;
- Some pavement sections should have had drains installed, but the presence of the drains was not confirmed in the field inspections; and
- Some pavement sections should and do have drains installed, but the drains do not appear to be functioning effectively.

The geographic distribution of the eighteen SPS-1 sites is illustrated in Figure 1. The originally intended site factorial for the experiment is shown in Table 2. Location data for the SPS-1 projects are given in Table 3.

In the wet-freeze-fine subgrade cell, two states were each to have built the two sets of twelve designs, to obtain "replicates" of these designs. These are not, however, replicates in the true sense of the word, as the sites are not identical in terms of the concomitant variable, truck traffic level, nor are their climates identical.

The site factorial shown in Table 2 represents what was supposed to have been built for the SPS-1 experiment. However, the Texas site turned out to have a fine, not a coarse, subgrade. So, although the locations remain unchanged, the site factorial for the actual SPS-1 experiment is as shown in Table 4.

The pavement designs in the core SPS-1 experiment constructed at the Alabama, Delaware, Florida, Iowa, Kansas, Nevada, New Mexico, and Ohio sites are shown in Table 5. The design at the Arizona, Arkansas, Louisiana, Michigan, Montana, Nebraska, Oklahoma, Texas, Virginia, and Wisconsin sites are shown in Table 6. Monitoring of the Louisiana SPS-1 project has ceased, and almost no performance data are available for it. So, there are effectively seventeen SPS-1 sites in service.

Climate Characterization

The climatic distribution of the SPS-1 sites was determined by extracting the latitude and longitude for each site from the LTPP database, searching the National Oceanic and Atmospheric Administration (NOAA) database for the weather station nearest the SPS-1 site, extracting the 30-year average monthly precipitation levels and average monthly temperatures for the weather station, and calculating the average annual precipitation and average annual temperature for each. These data are provided in Table 7. The distribution of the SPS-1 sites with respect to average annual precipitation and temperature is illustrated in Figure 2.

TABLE 1 SPS-1 design factorial

		Undrained			Drained	
Total Base Thickness, inches	Surface Thickness, inches	Dense-graded aggregate base	Asphalt-treated base	Asphalt-treated base over dense-graded aggregate	Permeable asphalt-treated base over aggregate	Asphalt-treated base over permeable asphalt-treated base
8	4	0113	0103	0105	0107	0122
	7	0101	0115	0117	0119	0110
12	4	0102	0116	0118	0120	0111
	7	0114	0104	0106	0108	0123
16	4				0121	0112
	7				0109	0124

The need for subsurface drainage can be quantified with respect to a design rainfall, that is, one of a given magnitude, duration, and frequency. For example, a 1-year, 1-hour rainfall is an amount of rainfall that at a particular location lasts 1 hour and occurs, on average, once a year. Rainfall frequency information is not easily accessed in tabular form but rather must be obtained from contour maps. The 1-year, 1-hour rainfalls for the SPS-1 and SPS-2 sites were determined from contour maps in Reference 2.

In the absence of rainfall frequency information, it is possible to estimate the 1-year, 1-hour rainfall as a function of the average annual precipitation, which is more readily known. As Figure 3 shows, there is an evident (although nonlinear) correlation between average annual precipitation and the 1-year, 1-hour rainfall for nearly all of the sites. The exceptions are the three SPS-1 sites closest to the Gulf coast (Texas, Louisiana, and Florida), for which the correlation curve seems to be shifted upward—that is, higher 1-year, 1-hour rainfall at those sites than for noncoastal sites with similar levels of average annual precipitation.

Test Section Layouts and Pavement Structures

The station limits, layer thicknesses, and material types for each of the SPS-1 test sections were extracted from the SPS_PROJECT_STATIONS and TST_L05B data tables in the LTPP database. The thicknesses in the TST_L05B table represent the LTPP regional support centers' best estimates of the as-built layer thicknesses and materials. The test section layouts and pavement layer data are given in Appendix A, along with information on which sections are supposed to be drained and which are not, and the locations of edgedrain outlets inspected in the field inspections conducted in late 2001 and early 2002.

The presence of filter fabric below the permeable asphalt-treated base in the SPS-1 test sections designed to be drained is summarized in Table 8. This summary is based on information in the TST_L05B and SPS1_LAYER data tables and the LTPP regional support centers' responses to an LTPP Data Analysis/Operations Feedback Report (KTH-1, 11 June 2002) submitted by the NCHRP 1-34C research team. In nearly all cases, no filter fabric was used below the permeable asphalt-treated base in test sections with the PATB/AGG base type. (The exceptions are the three Iowa SPS-1 sections, one of the three Kansas SPS-1 sections, and the three Texas SPS-1 sections with this base type.) On the other hand, in nearly all cases, filter fabric was used below the permeable asphalt-treated base in test sections with the ATB/PATB base type. (The exceptions are the three Kansas SPS-1 test sections with this base type.) There are also several cases of sections that do have a geotextile below the PATB, according to the regional support centers, although this is not reflected in the national LTPP database as of release 12.0.

Traffic Characterization

The 18-kip-equivalent single-axle (ESAL) levels at the SPS-1 sites were determined by extracting the following data from the LTPP database:

- ESAL estimates obtained from traffic monitoring during the experiment from the TRF_MON_EST_ESAL data table; and
- Axle load distributions obtained from traffic monitoring during the experiment from the TRF_MONITOR_AXLE_DISTRIBUTION data table.

Axle load distribution data were available for twelve of the eighteen SPS-1 sites. Data were not available for the sites in Alabama, Louisiana, Montana, Oklahoma, Texas, and Wisconsin.

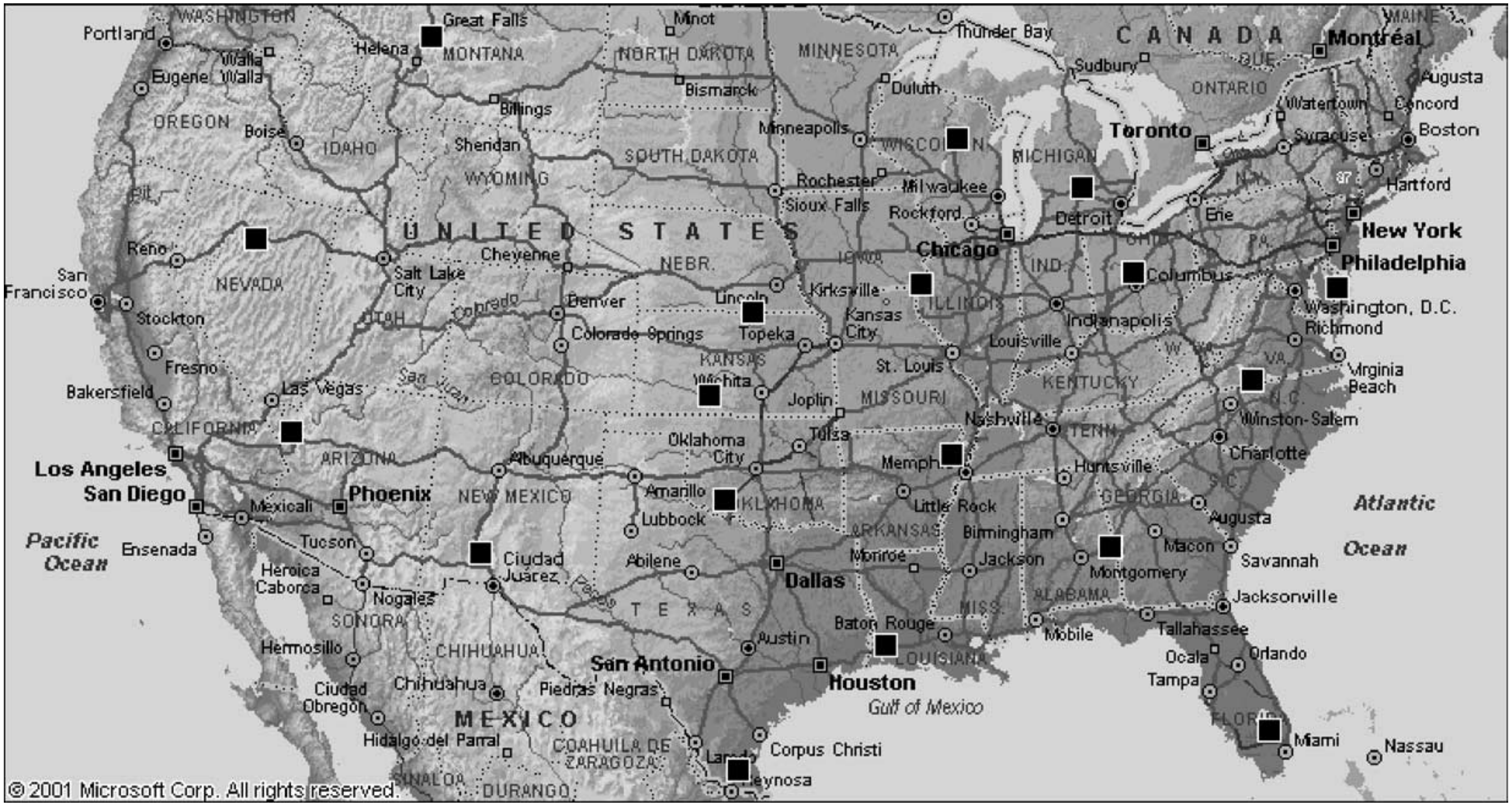

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Figure 1. SPS-1 sites.

TABLE 2 Intended SPS-1 site factorial

	Wet		Dry	
	Freeze	Nonfreeze	Freeze	Nonfreeze
Fine subgrade	IA, OH	AL	KS	NM
	VA, MI	LA	NE	OK
Coarse subgrade	DE	FL	NV	TX
	WI	AR	MT	AZ

TABLE 3 SPS-1 location data

SHRP ID	State	County	Nearby city or town	Route	Latitude	Longitude
010100	AL	Lee	Opelika	US 280	32.61	85.25
040100	AZ	Mohave	Kingman	US 93	35.39	114.26
050100	AR	Craighead	Jonesboro	US 63	35.72	90.58
100100	DE	Sussex	Ellendale	US 113	38.79	75.44
120100	FL	Palm Beach	Coral Springs	US 27	26.33	80.69
190100	IA	Lee	Burlington	US 61	40.42	91.25
200100	KS	Kiowa	Greensburg	US 54	37.60	99.25
220100	LA	Calcasieu	Lake Charles	US 171	30.33	93.20
260100	MI	Clinton	Lansing	US 27	42.99	84.52
300100	MT	Cascade	Great Falls	I-15	47.41	111.53
310100	NE	Thayer	Hebron	US 81	40.07	97.62
320100	NV	Lander	Battle Mountain	I-80	40.69	117.01
350100	NM	Doña Ana	Las Cruces	I-25	32.68	107.07
390100	OH	Delaware	Delaware	US 23	40.38	83.06
400100	OK	Comanche	Lawton	US 62	34.64	98.66
480100	TX	Hidalgo	McAllen	US 281	26.74	98.11
510100	VA	Pittsylvania	Danville	US 29	36.66	79.37
550100	WI	Marathon	Wausau	SR 29	44.87	89.29

TABLE 4 Actual SPS-1 site factorial

	Wet		Dry	
	Freeze	Nonfreeze	Freeze	Nonfreeze
Fine subgrade	IA, OH	AL	KS	NM
	VA, MI	LA	NE	OK, TX
Coarse subgrade	DE	FL	NV	
	WI	AR	MT	AZ

ESALs were calculated for the years in which axle load distribution data were available, using: (1) the number of axles reported in each load range in the distribution and (2) load equivalency factors calculated as a function of Structural Number (in turn calculated from as-built layer thicknesses and typical structural coefficients for asphalt concrete, treated and untreated base, and treated and untreated subbase). For years during the experiment in which axle load distribution data were not available, ESAL estimates from TRF_MON_EST_ESAL table were used if available.

In a few cases, linear interpolations of annual ESALs were necessary for years in which no axle load distribution or ESAL data were available. It was also necessary in a few cases to extrapolate a year or two before or after the years for which data were available. A growth rate of 5 percent was used for these extrapolations.

From the annual ESAL estimates for the different test sections at each site, the average annual ESALs for the site were calculated. The average annual ESAL estimates for each site were used to calculate accumulated ESAL estimates from the date of opening to traffic to several dates of profile, rutting, and cracking measurements. The measurement dates were those on which measurements were obtained for most or all of the test sections at the site. The estimated accumulated

TABLE 5 Core SPS-1 test sections built at the Alabama, Delaware, Florida, Iowa, Kansas, Nevada, New Mexico, and Ohio sites

		Undrained			Drained	
Total Base Thickness, inches	Surface Thickness, inches	Dense-graded aggregate base	Asphalt-treated base	Asphalt-treated base over dense-graded aggregate	Permeable asphalt-treated base over aggregate	Asphalt-treated base over permeable asphalt-treated base
8	4		0103	0105	0107	
	7	0101				0110
12	4	0102				0111
	7		0104	0106	0108	
16	4					0112
	7				0109	

ESALs to each of the selected measurement dates, for each site with data available, are provided in Appendix A.

The age of each SPS-1 site and the accumulated flexible pavement ESALs for each site with traffic data available, as of the latest date of condition measurements available for this study, are shown in Table 9. Also shown is the accumulated ESALs divided by the age, which gives a rough estimate of the average annual ESAL level during the time that each site has been in service. The annual and accumulated ESAL levels are fairly low at all of the SPS-1 sites.

The ages and accumulated ESALs at the SPS-1 sites are also illustrated in Figure 4. The vertical scale of this graph was chosen to be compatible with the range of rigid pavement ESALs for the SPS-2 sites (shown in Chapter 3). Most of the SPS-1 pavements had carried considerably less truck traffic at the time of the analysis than most of the SPS-2 pavements.

SPS-1 Construction

Some information on construction of the SPS-1 sites is available in Reference 3 and in the construction reports prepared by the LTPP regional support centers. At most of the SPS-1 sites, one or more problems or deviations occurred during construction. However, most of the construction reports contain little information on the installation of the drainage systems. The information on construction deviations available in Reference 3 is summarized in Table 10.

FIELD INSPECTIONS OF DRAINS AT SPS-1 SITES

Video inspections of the drains at the SPS-1 and SPS-2 sites were conducted in late 2001 and early 2002 under an FHWA

TABLE 6 Core SPS-1 test sections built at the Arizona, Arkansas, Louisiana, Michigan, Montana, Nebraska, Oklahoma, Texas, Virginia, and Wisconsin sites

		Undrained			Drained	
Total Base Thickness, inches	Surface Thickness, inches	Dense-graded aggregate base	Asphalt-treated base	Asphalt-treated base over dense-graded aggregate	Permeable asphalt-treated base over aggregate	Asphalt-treated base over permeable asphalt-treated base
8	4	0113				0122
	7		0115	0117	0119	
12	4		0116	0118	0120	
	7	0114				0123
16	4				0121	
	7					0124

TABLE 7 Average annual precipitation and temperature levels for weather stations nearest SPS-1 sites

SPS-1 Site				Nearest Weather Station					
State	State Code	Latitude (degrees)	Longitude (degrees)	ID	Name	Latitude (degrees)	Longitude (degrees)	Average Annual Precipitation (inches)	Average Annual Temperature (degrees F)
AL	01	32.61	85.25	014502	Lafayette	32.54	85.24	57.56	62.60
AZ	04	35.39	114.26	267369	Searchlight	35.28	114.55	7.42	63.30
AR	05	35.72	90.58	033734	Jonesboro 4 N	35.53	90.42	47.19	60.60
DE	10	38.79	75.44	182523	Denton 2 E	38.53	75.48	42.55	55.90
FL	12	26.33	80.69	081654	Clewiston US ENG	26.45	80.55	45.01	74.00
IA	19	40.42	91.25	135796	Mount Pleasant 1SSW	40.57	91.33	36.98	49.80
KS	20	37.60	99.25	144333	Kinsley	37.55	99.25	24.51	54.90
LA	22	30.33	93.20	162361	De Quincy 4 N	30.31	93.26	58.20	66.20
MI	26	42.99	84.52	207280	Saint Johns	43.01	84.33	31.39	46.20
MT	30	47.41	111.53	242857	Fairfield	47.37	111.59	12.46	42.90
NE	31	40.07	97.62	251680	Clay Center 6 ESE	40.30	97.56	26.98	49.90
NV	32	40.69	117.01	263245	Golconda	40.57	117.29	7.58	50.00
NM	35	32.68	107.07	291286	Caballo Dam	32.54	107.18	10.17	60.20
OH	39	40.38	83.06	334942	Marion 2 N	40.37	83.08	36.91	49.20
OK	40	34.64	98.66	349629	Wichita MT WL REF	34.44	98.43	31.12	59.60
TX	48	26.74	98.11	413063	Fulfurrias	27.14	98.08	25.88	71.60
VA	51	36.66	79.37	441614	Chatham	36.49	79.24	44.39	54.80
WI	55	44.87	89.29	475364	Merrill	45.11	89.41	32.21	41.00

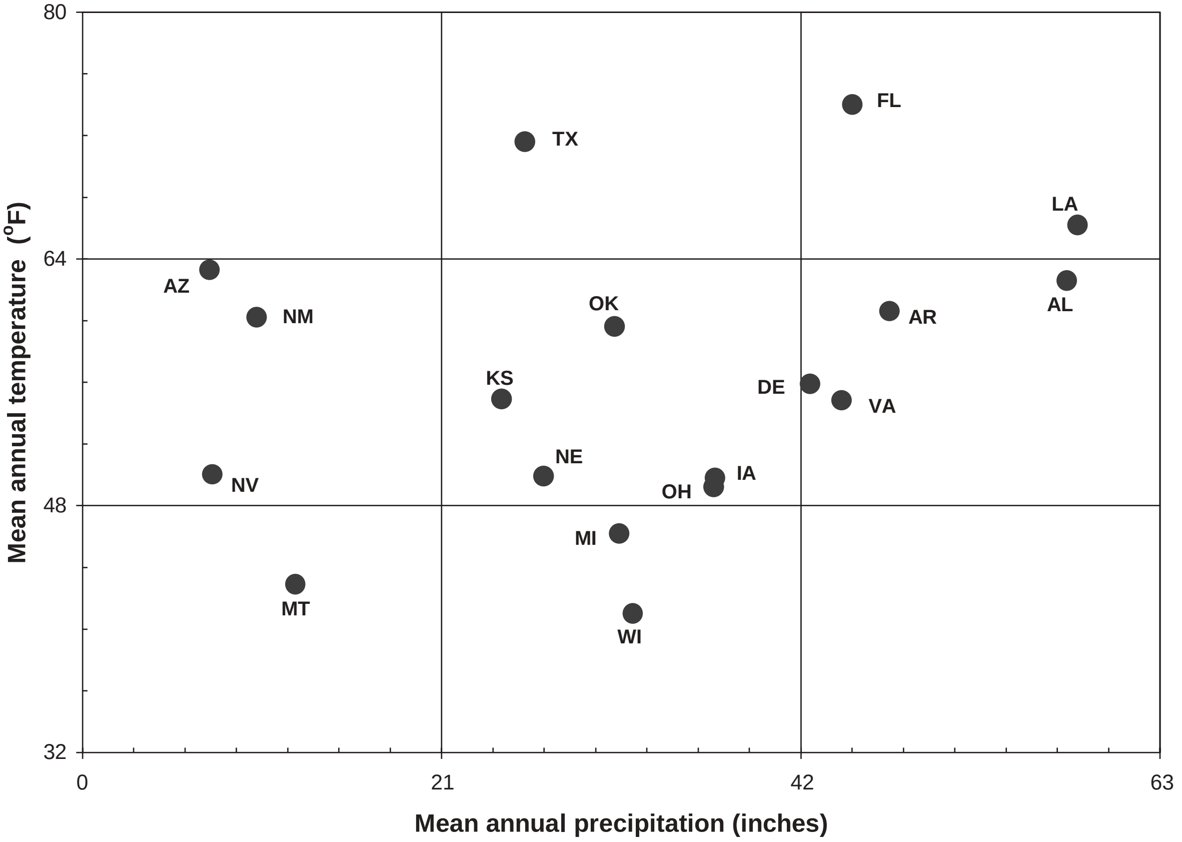

Figure 2. Distribution of SPS-1 sites with respect to precipitation and temperature.

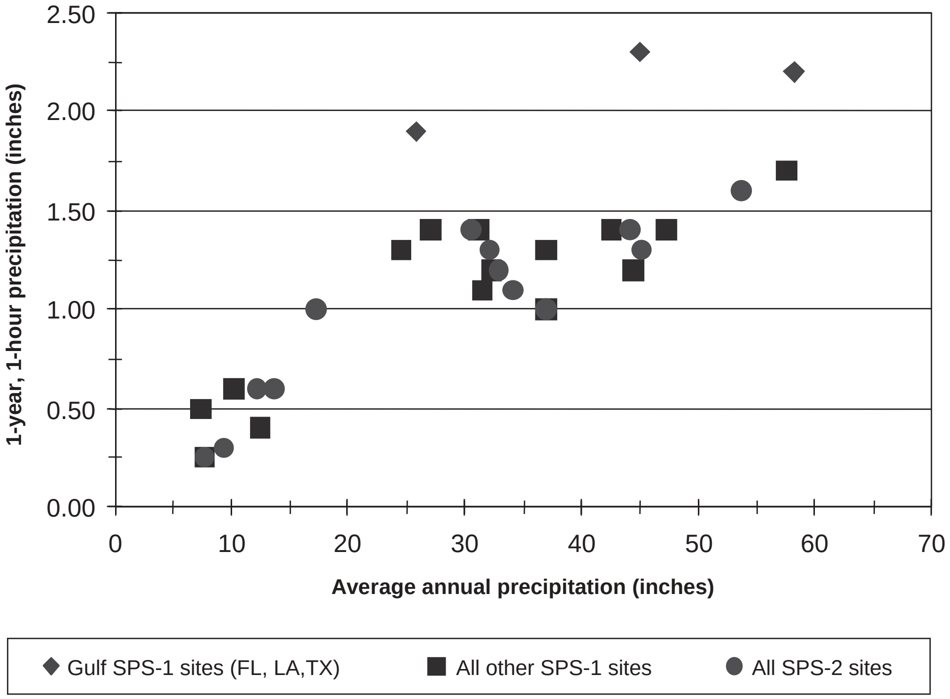

Figure 3. 1-year, 1-hour frequency precipitation rate versus average annual precipitation for SPS-1 and SPS-2 sites.

contract with NCHRP support. The completed data forms for each site were furnished to the NCHRP Project 1-34C research team for use in this study. Highlights of the inspections are summarized in Appendix A. The test section layout diagrams in Appendix A show the locations of the edgedrain outlets inspected.

Observations on Results of Field Inspections

A summary of the drains inspected and not inspected is given in Table 11. In cases where an outlet was located outside the limits of any test section, it was assumed to be associated with the nearest test section.

The field inspections reveal some surprising things about the drainage installations at several of the SPS-1 sites.

- First, there were some instances found of test sections that should not be drained but at which lateral outlets were found and marked for inspection. These are indicated by a "*y*" in some cells in the first six test section columns in Table 11. There are several possible explanations for these discrepancies:
  - (a) Longitudinal subdrains with lateral outlets were not placed in the test section during construction, or
  - (b) Subdrains with outlets were placed during construction but could not be located and marked for inspection, or
  - (c) Subdrains with outlets were placed and could have been located but were not marked for inspection, or
  - (d) Subdrains with outlets were placed and were marked for inspection but were not inspected.
- Second, there were several instances found of test sections that should be drained (test sections numbered 0107 through 0112 or 0119 through 0124, depending on the site), but at which no lateral outlets within or near the sections were found or marked for inspection. These instances are indicated by an "n" rather than a "y" in some cells in the last six test section columns in Table 11.

These discrepancies were reported to LTPP in an LTPP Data Analysis/Operations Feedback Report (KTH-3, 11 June 2002) submitted by the NCHRP 1-34C research team. The responses received from the LTPP regional support centers are summarized below.

SPS-1 test sections designed to be undrained, but drains were found and inspected:

- Iowa 0102, 0103, 0104, 0105, and 0106—Design plans show that outlets were planned in each of these sections. In section 0103, the outlet was to be placed on the right side of the road; in the other four sections, the outlet was to be on the left side of the road. No as-built records are available to confirm whether or not these outlets are present.

TABLE 8 Presence of filter fabric below permeable asphalt-treated base in SPS-1 sections designed to be drained

	Base Type					
	Permeable asphalt-treated base over aggregate			Asphalt-treated base over permeable asphalt-treated base		
	Section number					
State	0107	0108	0109	0110	0111	0112
AL 01	no	no	no	yes	yes	yes
DE 10	no	no	no	yes	yes	yes
FL 12	no	no	no	yes	yes	yes
IA 19	yes*	yes*	yes*	yes*	yes*	yes*
KS 20	yes*	no	no	no	no	no
LA 22	no	no	no	yes	yes	yes
NV 32	no	no	no	yes*	yes*	yes*
NM 35	no	no	no	yes	yes	yes
OH 39	no	no	no	yes*	yes*	yes*
	Section number					
	0119	0120	0121	0122	0123	0124
AZ 04	no	no	no	yes*	yes*	yes*
AR 05	no	no	no	yes	yes	yes
MI 26	no	no	no	yes	yes	yes
MT 30	no	no	no	yes*	yes*	yes*
NE 31	no	no	no	yes*	yes*	yes*
OK 40	no	no	no	yes	yes	yes
TX 48	yes	yes	yes	yes	yes	yes
VA 51	no	no	no	yes	yes	yes
WI 55	no	no	no	yes	yes	yes

* The regional support center reports that geotextile was placed below the PATB, although this is not reflected in LTPP database release 12.0.

- Michigan 0115, 0117, and 0118—Design plans show no outlets planned for the first two of these sections; they show one outlet planned for the third section, but the station is not indicated. No as-built records are available to confirm whether or not these outlets are present.
- Ohio 0101, 0102, 0103, 0104, 0105, and 0106—Design plans show that outlets were planned, for both sides of the road, in sections 0101 and 0102. No as-built records are available to confirm whether or not these outlets are present.
- Virginia 0114, 0115, and 0116—No edge drains were installed and are not present. Edge drains may be present outside of the section limits and may be the reason the drainage inspector found outlets. The stationing should be checked to verify the correct location of the outlets.

SPS-1 test sections designed to be drained, but drains were not found:

- AZ 0124—According to construction information, this section has three drainage outlets; but, due to the overgrown bush and the presence of rattlesnakes, these outlets were not inspected.
- FL 0108 and 0111—The Florida SPS-1 laterals have been damaged by farming traffic. The missing laterals are most likely buried and not operational.
- Iowa 0107, 0110, and 0112—Design plans show that outlets were planned in each of these sections. In section 0107, the outlet was to be on the left side of the road; in sections 0110 and 0112, outlets were to be placed on both the left and right sides of the road. No as-built records are available to confirm whether or not these outlets are present.
- Kansas 0107, 0109, 0110, and 0112—Design plans show that outlets were planned on both the left and right sides of the road in each of the sections. No as-built records are available to confirm whether or not these outlets are present.
- Louisiana 0119 and 0122—Louisiana SPS-1 was already at close-out status at the time of inspection. Laterals were retrofitted in all sections with PATB layer. The missing laterals are most likely buried and not functional.

TABLE 9 Age and accumulated flexible pavement equivalent standard axle loads (ESALs) of SPS-1 sites at time of analysis

State	Age, years	Accumulated flexible pavement ESALs, millions	Accumulated ESALs divided by age
Alabama	8.04	Data unavailable	
Arizona	7.75	1.93	0.25
Arkansas	6.39	2.66	0.42
Delaware	4.60	2.01	0.44
Florida	4.86	2.25	0.46
Iowa	7.99	1.22	0.15
Kansas	7.53	1.88	0.25
Louisiana	2.36	Data unavailable	
Michigan	4.87	0.32	0.07
Montana	2.62	Data unavailable	
Nebraska	5.79	0.56	0.10
Nevada	5.62	3.01	0.54
New Mexico	5.51	0.84	0.15
Ohio	5.44	0.39	0.07
Oklahoma	3.51	Data unavailable	
Texas	3.89	Data unavailable	
Virginia	4.95	1.66	0.33
Wisconsin	2.60	Data unavailable	
Average	**5.94**	**1.56**	**0.27**

- Michigan 0119, 0120, 0122, and 0124—Design plans show that three outlets were planned in each of these sections. No as-built records are available to confirm whether or not these outlets are present.
- New Mexico 0109—The project is supposed to have concrete headwalls. However, the State Coordinator could not locate the headwalls in the locations where he did not find the lateral [sic: presumably, where the lateral should have been]. This is an indication that the headwalls and lateral are buried.
- Ohio 0107 and 0109—Design plans show that section 0107 had two outlets planned, on both sides of the road. Design plans do not show any outlets for section 0109. No as-built records are available to confirm whether or not these outlets are present.
- Virginia 0119—Edgedrains were installed and are present. The drainage inspector must have missed the outlet.
- Wisconsin 0119, 0120, 0121, 0122, 0123, and 0124—Designs plans indicate that two or three outlets were planned in each of these sections. Outlets in sections 0120 and 0122 were planned on the left side of the road; outlets in the other sections were planned on both sides of the road. No as-built records are available to confirm whether or not these outlets are present. [Note: the video inspection contractor reported that LTPP regional center support personnel visited the Wisconsin SPS-1 site and could not locate any lateral outlets to mark on either occasion. However, Wisconsin DOT personnel and a research team member who visited the site confirm that the outlets are present.]

Test sections designed to be drained but for which drainage outlets could not be located were not used in this analysis of the effects of drainage on pavement performance. Similarly, test sections designed to be undrained but at which lateral outlets were found and inspected also were not used in the analysis presented in this report.

After reviewing the forms summarizing the video inspections of the drainage installations, the 1-34C research team made a subjective assessment of whether the quality of drainage functioning in each test section was “good” or “poor.” The ratings assigned are summarized in Table 12. Conditions that garnered a “poor” rating included lateral outlets being buried or fully blocked with silt, gravel, or other debris; longitudinal drains being fully blocked; or a considerable amount of water standing in longitudinal drains and not flowing out.

Longitudinal drains and lateral outlets in a pavement structure that has been in service some years are never pristine; there is nearly always some silt accumulation and some rodents and their nests. Whether or not there is enough material present to block the flow of water in the event of a storm—or whether the flow of water caused by a storm would clear out some or all of this material—remains a matter of judgment, until someone investigates this by conducting video inspections before and after storms. In general, if the amount of mate-

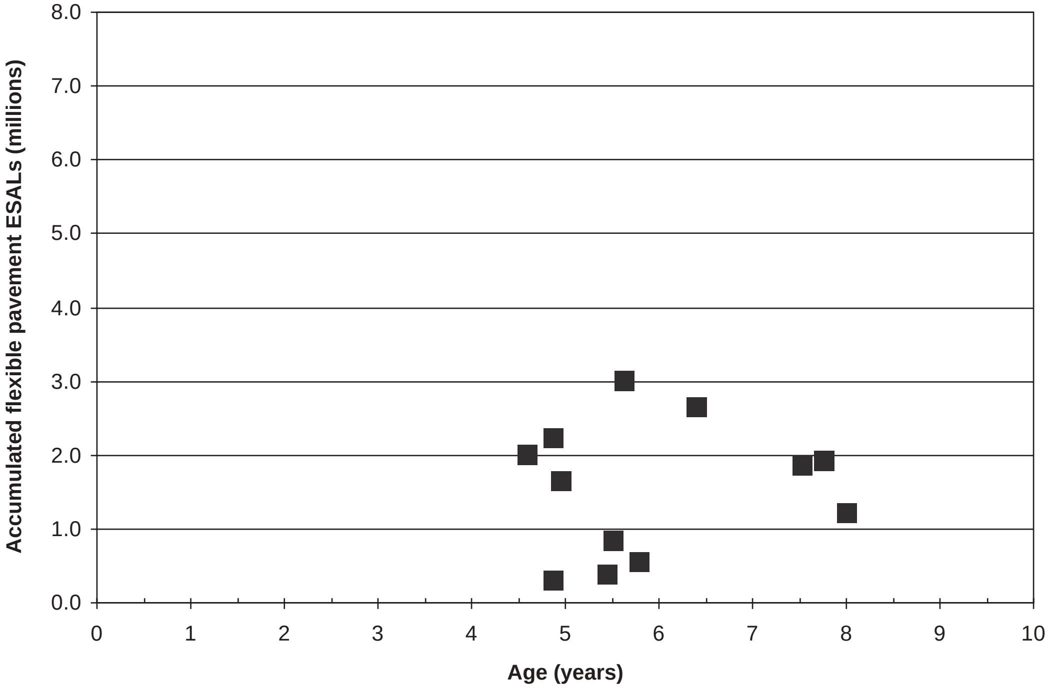

Figure 4. Age versus accumulated flexible ESALs for SPS-1 sites with traffic data available.

rial described as being present did not seem sufficient to block the flow of water, a "good" rating was assigned.

In Table 12, a question mark alone in a cell indicates that no rating can be assigned because no laterals were inspected within the test section. A question mark with an asterisk indicates that a lateral was found and inspected visually, but the video camera could not be inserted in the lateral to inspect the interior of the longitudinal drain. In some cases this was because the inner diameter of the lateral was too small. In other cases this was because rodent screens were placed too far up in the lateral, out of arm's reach, and could not be removed so that the camera could pass.

EFFECTS OF DRAINAGE ON SPS-1 ASPHALT PAVEMENT PERFORMANCE

Tables 5 and 6 show that the following test section comparisons may be conducted to assess the effects of drainage on pavement performance in the SPS-1 experiment, holding asphalt concrete thickness and base thickness constant.

(A) Undrained dense-graded aggregate (AGG) versus dense asphalt-treated base over drained permeable asphalt-treated base (ATB/PATB)

- 0101 versus 0110: 7-inch asphalt concrete over 8-inch base
- 0102 versus 0111: 4-inch asphalt concrete over 12-inch base
- 0113 versus 0122: 4-inch asphalt concrete over 8-inch base
- 0114 versus 0123: 7-inch asphalt concrete over 12-inch base

(B) Undrained dense asphalt-treated base (ATB) versus permeable asphalt-treated base over dense-graded aggregate (PATB/AGG):

- 0103 versus 0107: 4-inch asphalt concrete over 8-inch base
- 0104 versus 0108: 7-inch asphalt concrete over 12-inch base
- 0115 versus 0119: 7-inch asphalt concrete over 8-inch base
- 0116 versus 0120: 4-inch asphalt concrete over 12-inch base

(C) Undrained dense asphalt-treated base over dense-graded aggregate (ATB/AGG) versus permeable asphalt-treated base over dense-graded aggregate (PATB/AGG):

- 0105 versus 0107: 4-inch asphalt concrete over 8-inch base
- 0106 versus 0108: 7-inch asphalt concrete over 12-inch base
- 0117 versus 0119: 7-inch asphalt concrete over 8-inch base

TABLE 10 SPS-1 construction problems and deviations (from Reference 3)

SHRP ID	State	Problem or Deviation
010100	AL	Mechanical problem with paver; construction joint placed in section 0111. Deformations occurred on top of the PATB[1]. DGAB[2] contained excess minus 200 material.
040100	AZ	Rain delays during subgrade preparation. Fill material pumped, but was replaced prior to paving. Section 0122 included a layer of DGAB below the PATB. DGAB for sections 0119 and 0122 did not meet the gradation requirements.
050100	AR	Rain caused construction delays, but surfaces were allowed to dry prior to resuming construction. DGAB thickness on section 0114 was less than half of the required value. Many other sections were also less than the design value. The stability of the HMA[3] mixture was less than the specified value.
100100	DE	High water table along the project. Ditches were shallow, so outlets of drains were not placed at the 76-m spacing. The number 4 sieve from the gradation tests for the HMA surface did not meet the project specifications.
120100	FL	Rain delays caused the DGAB to be reworked multiple times. The number 4 sieve from the gradation tests for the HMA surface did not meet the project specification.
190100	IA	Multiple rain delays, but surfaces were allowed to dry and were reworked. PATB “rolled out” on the sides, which resulted in the placement of an extra lift to meet the thickness requirement. The number 4 sieve from the gradation tests for the HMA binder layer exceeded the project requirements.
200100	KS	Excessive moisture in the subbase, which caused difficulty in compacting the material. Fly ash was added to the subbase layer for stabilization purposes.
220100	LA	Test sections for thickness cells 1 to 12 rather than 13 to 24 were built. Rain delays. Subgrade was stabilized with cement. Fabric did not meet overlay requirements. Aggregate in drainage trenches contained fines. DGAB was compacted in one lift. Select material was used at site to achieve the final elevation.
260100	MI	None noted.
300100	MT	None noted.
310100	NE	Three test sections were constructed over culverts. Rain delays. The minus 200 material for the PATB exceeded the project requirements.
320100	NV	HMA facility breakdown. High air voids reported in the ATB[4] prior to plant breakdown. Localized tenderness problem noted.
350100	NM	HMA facility breakdown. High air voids reported in the ATB prior to plant breakdown. Localized tenderness problem noted.
390100	OH	Fill material placed on all sections. DGAB thickness was much larger than the planned thickness. The number 4 sieve for the HMA surface did not meet the project requirements.
400100	OK	The number 4 sieve for the HMA surface did not meet the project requirements. One of the two ATB lifts exceeded the project thickness requirements.
480100	TX	Transverse interceptor drains not installed along the project.
510100	VA	Subgrade treated with cement. The number 4 sieve for the HMA surface did not meet the project requirements.
550100	WI	None noted.

[1] Permeable asphalt-treated base
[2] Dense-graded aggregate base.
[3] Hot mix asphalt.
[4] Asphalt-treated base.

TABLE 11 SPS-1 test-section sections with drainage outlets inspected with video

	Test Section Numbers											
	0101 and 0113	0102 and 0114	0103 and 0115	0104 and 0116	0105 and 0117	0106 and 0118	0107 and 0119	0108 and 0120	0109 and 0121	0110 and 0122	0111 and 0123	0112 and 0124
	Base Type											
	Dense-graded aggregate		Asphalt-treated base		Asphalt-treated base over dense-graded aggregate		Permeable asphalt-treated base over aggregate			Asphalt-treated base over permeable asphalt-treated base		
State	Undrained						Drained					
AL							y[1]	y	y	y	y	y
AZ							y	y	y	y	y	n[2]
AR							y	y	y	y	y	y
DE							y	y	y	y	y	y
FL							y	n	y	y	n	y
IA		*y*[3]	*y*	*y*	*y*	*y*	n	y	y	n	n	y
KS							n	y	n	n	y	n
LA							n	y	y	n	y	y
MI			*y*		*y*	*y*	n	n	y	n	y	n
MT							y	y	y	y	y	y
NE							y	y	y	y	y	y
NV							y	y	y	y	y	y
NM							y	y	n	y	y	y
OH	*y*	*y*	*y*	*y*	*y*	*y*	n	y	n	y	y	y
OK							y	y	y	y	y	y
TX							y	y	y	y	y	y
VA		*y*	*y*	*y*			n	y	y	y	y	y
WI							n	n	n	n	n	n

[1] y = in unshaded cells, subdrains found and inspected
[2] n = subdrains not found or found but not inspected.
[3] *y* = in shaded cells, drains found and inspected, even though according to the experiment design the section should not have drains.

- 0118 versus 0120: 4-inch asphalt concrete over 12-inch base

The test sections on 16-inch-thick base (numbered 0109, 0112, 0121, and 0124) are not directly useful in this analysis of the effects of drainage on pavement performance, since all of these sections were designed to have drains, and there are no corresponding undrained designs in the experiment. However, the test sections on 16-inch-thick-base are anticipated to be useful in future analyses differentiating the effects of structural capacity and subdrainage on performance.

The sites with test sections useful to each of the above comparisons were identified by combining the information about which test sections had drainage inspected (Table 11) with the information about the subjective ratings of drainage functioning (Table 12).

For each of the three sets of comparisons listed, and for each pavement performance indicator considered (International Roughness Index [IRI], rutting, and cracking), paired *t*-tests were conducted to determine whether or not the mean difference between the undrained and drained test section pairs was significant. Three paired *t*-tests were conducted each time:

- For the subset of test section pairs with drainage functioning rated as good (denoted by G in the column “Drainage functioning” in Tables 13 through 21),
- For the subset of test section pairs rated as poor (denoted by P in the column “Drainage functioning” in Tables 13 through 21), and
- For all valid test section pairs regardless of drainage functioning (denoted by G, P, or ? in Tables 13 through 21).

The test section pairs excluded from these comparisons were:

- Those that had subdrainage outlets located and inspected in the section that was designed to be undrained (denoted by X in Tables 13 through 21), and

TABLE 12 Subjective ratings of drainage functioning at SPS-1 test sections based on video inspection results

	Test Section ID											
	0101 and 0113	0102 and 0114	0103 and 0115	0104 and 0116	0105 and 0117	0106 and 0118	0107 and 0119	0108 and 0120	0109 and 0121	0110 and 0122	0111 and 0123	0112 and 0124
	Base Type											
	Dense-graded aggregate		Asphalt-treated base		Asphalt-treated base over dense-graded aggregate		Permeable asphalt-treated base over aggregate			Asphalt-treated base over permeable asphalt-treated base		
State	Undrained						Drained					
AL							G[1]	G	G	G	G	G
AZ							G	G	G	G	G	?[2]
AR							P[3]	P	P	P	P	P
DE							G	G	G	G	G	G
FL							P	?	P	P	?	P
IA		P	G	P	P	G	?	G	P	?	?	P
KS							?	P	?	?	?*[4]	?
LA							?	P	P	?	?	?
MI						P	?	?	P	?	P	?
MT							G	G	G	G	G	G
NE							G	G	G	G	G	G
NV							P	P	P	P	P	P
NM							P	P	?	P	P	P
OH	G	G	G	G		P	?	G	?	G	G	G
OK							?*	?*	?*	?*	?*	?*
TX							P	P	P	P	P	P
VA		G	G	G			?	G	G	G	G	G
WI							?	?	?	?	?	?

[1] G = Drainage function rated as good.
[2] ? = Drainage outlets not found.
[3] P = Drainage function rated as poor.
[4] ?* = Camera could not be inserted.

- Those lacking measurement data for one or both of the test sections (denoted by --- in Tables 13 through 21).

The difference in the performance measures (IRI, rutting, or cracking) for each test section pair is calculated as the measured value for the undrained section minus the measured value for the drained section. Thus, a positive difference indicates that the measured value was greater in the undrained section, and a negative difference indicates that the measured value was greater in the drained section.

The mean difference for all the pairs considered is the sum of the pairwise differences divided by the number of pairs. Whether or not the mean difference is significant (at a selected significance level, e.g., 95 percent) is determined by calculating the lower and upper limits of (95-percent) confidence interval around the mean difference. If zero is not contained within the lower and upper limits of the confidence interval, the mean difference can be concluded, with 95 percent confidence, to be significantly different from zero.

Effect of Drainage on Asphalt Pavement Roughness (IRI) Development

For each SPS-1 site, IRI data were extracted from the MON_PROFILE_MASTER table in the LTPP database. An IRI for each run was calculated as the average of the run's left and right wheelpath IRIs. An average IRI for each testing date was then calculated as the average of the run IRIs for that date—most often five runs, but sometimes as few as one or as many as fifteen.

The expectation is that IRI will tend to increase over time, as the pavement deteriorates. However, IRI does not always increase steadily over time. Sometimes the IRI of a test section is lower than the IRI measured on the same test section a year earlier, a month earlier, or even a day earlier. Physical reasons why IRI might decrease from one testing date to the next. include the following (from Reference 4):

- Rehabilitation or maintenance between testing dates;
- Seasonal variation;
- Measurement in different paths;
- Different starting locations;
- Spikes in the data caused by reflection of light from the white paint stripe at the start of a test section; or
- Problems with the profilometer electronics, sensors, or distance measurement.

However, it is not necessarily true that an IRI decrease, or an IRI increase for that matter, always has a physical explanation. Some portion of the variation seen in IRI data is random variation. That is, some fluctuations in IRI, both upward and downward, are not significantly different from no change at all.

The first available IRI is not necessarily the IRI immediately after opening to traffic. The first testing date for which IRI data are available for all or most of the test sections at a site may be a year or more after the opening date. (Note that the date of opening to traffic is shown for each site in the ESAL calculation summary in Appendix A.) Similarly, the latest IRI measurements used in the analysis are not necessarily those for the latest IRI measurement date at any one test section at a site, but rather those for the latest IRI measurement date for which measurements are available for most or all of the sections at a site. The IRI histories of the test sections at each SPS-1 site are shown in Appendix A. Note that no IRI history is shown for the Louisiana SPS-1 site because only one set of IRI data, from 1997, is available for that site.

The comparisons of IRI change between drained and undrained sections of matching designs are shown in Tables 13, 14, and 15. Which comparisons were deemed possible was assessed on the basis of the drainage detection and drainage functioning information summarized in Tables 11 and 12.

Table 13 shows the comparisons of undrained dense-graded aggregate base (AGG) versus dense asphalt-treated base over drained permeable asphalt-treated base (ATB/PATB). For drained ATB/PATB sections with drainage functioning subjectively rated as good, the change in IRI was significantly less than in the undrained AGG sections of corresponding design. (This is indicated by a positive mean difference in change in IRI, undrained—drained, that is significantly different from zero). The same was true when all drained ATB/PATB sections combined (good, poor, and unknown drainage functioning) were compared with the corresponding undrained AGG sections. When only drained ATB/PATB sections with drainage functioning rated as poor were compared with corresponding undrained AGG sections, no significant difference in change in IRI was detected.

Table 14 shows the comparisons of undrained dense asphalt-treated base (ATB) versus drained permeable asphalt-treated base over aggregate (PATB/AGG). For drained PATB/AGG sections with drainage functioning rated as good, the change in IRI was slightly, but not significantly, greater than in the corresponding undrained ATB sections. (This is indicated by a negative mean difference, undrained—drained, that is not significantly different from zero). The same was true for drained PATB/AGG sections with drainage functioning rated as poor, and for all drained PATB/AGG sections regardless of drainage functioning.

Table 15 shows the comparisons of undrained dense asphalt-treated base over dense-graded aggregate (ATB/AGG) versus drained permeable asphalt-treated base over aggregate (PATB/AGG). For drained PATB/AGG sections with drainage functioning rated as good, the change in IRI was slightly, but not significantly, less than in the corresponding undrained ATB/AGG sections. The same was true for all drained PATB/AGG sections considered together, regardless of drainage functioning. For drained PATB/AGG sections with drainage functioning rated as poor, the change in IRI was slightly greater, but again not significantly so, than in the corresponding undrained ATB/AGG sections.

Effect of Drainage on Asphalt Pavement Rutting Development

The rutting histories of the test sections at each SPS-1 site are shown in Appendix A. The estimated accumulated ESALs corresponding to the most recent rutting measurements are reported in Appendix A. The accumulated ESAL values are slightly different from those reported for the IRI histories, since rutting and IRI were measured on different dates. Rutting histories for the Florida and Louisiana SPS-1 sites are not shown because of the limited data available.

The comparisons of rutting change between drained and undrained sections of matching designs are shown in Tables 16, 17, and 18. Which comparisons were deemed possible was assessed on the basis of the drainage detection and drainage functioning information summarized in Tables 11 and 12.

Table 16 shows the comparisons of undrained dense-graded aggregate base (AGG) versus dense asphalt-treated base over drained permeable asphalt-treated base (ATB/PATB). For drained ATB/PATB sections with drainage functioning subjectively rated as good, the change in rutting was slightly, but not significantly, less than in the undrained AGG sections of corresponding design. The same was true for drained ATB/PATB sections with drainage functioning rated as poor, and for all drained ATB/PATB sections combined (good, poor, and unknown drainage functioning).

Table 17 shows the comparisons of undrained dense asphalt-treated base (ATB) versus drained permeable asphalt-treated base over aggregate (PATB/AGG). For drained PATB/AGG sections with drainage functioning rated as good, the change in rutting was slightly, but not significantly, less than in the corresponding undrained ATB sections. The same was true for drained PATB/AGG sections with drainage functioning rated as poor and for all drained PATB/AGG sections combined regardless of drainage functioning.

TABLE 13 Change in International Roughness Index (IRI) in SPS-1 undrained dense-graded aggregate (AGG) base sections versus drained asphalt-treated base over drained permeable asphalt-treated base (ATB/PATB) sections

	IRI		Age, years	Drainage functioning	Difference in IRI		
	AGG	ATB/PATB			All	Good	Poor
Site	**0101**	**0110**					
AL 01	0.086	0.002	5.37	G[1]	0.084	0.084	
DE 10	0.010	-0.055	3.49	G	0.065	0.065	
FL 12	-0.071	-0.004	3.62	P[2]	-0.067		-0.067
IA 19	0.636	0.576	6.29	?[3]	0.060		
KS 20	0.411	0.198	4.27	?	0.213		
NV 32	-0.008	-0.009	3.14	P	0.001		0.001
NM 35	0.253	0.005	4.15	P	0.248		0.248
OH 39	2.682	0.125	0.37	X[4]			
Site	**0102**	**0111**					
AL 01	0.470	0.027	5.18	G	0.443	0.443	
DE 10	0.116	-0.023	3.49	G	0.139	0.139	
FL 12	0.002	-0.019	3.62	?	0.021		
IA 19	1.713	0.338	6.29	X			
KS 20	-0.136	0.137	4.27	?	-0.273		
NV 32	0.210	-0.009	3.14	P	0.219		0.219
NM 35	0.333	0.128	4.15	P	0.205		0.205
OH 39	0.315	0.097	0.37	X			
Site	**0113**	**0122**					
AZ 04	0.184	0.102	6.89	G	0.082	0.082	
AR 05	0.162	0.230	5.54	P	-0.068		-0.068
LA 22	---[5]	---	---	---			
MI 26	---	---	---	---			
MT 30	0.034	-0.036	1.64	G	0.070	0.070	
NE 31	0.082	0.056	3.93	G	0.026	0.026	
OK 40	0.108	0.042	3.13	?	0.066		
TX 48	0.035	-0.002	3.63	P	0.037		0.037
VA 51	0.420	-0.050	3.62	G	0.470	0.470	
WI 55	0.100	0.073	2.40	?	0.027		
Site	**0114**	**0123**					
AZ 04	0.201	0.052	6.89	G	0.149	0.149	
AR 05	0.150	0.157	5.54	P	-0.007		-0.007
LA 22	---	---	---	---			
MI 26	---	0.057	3.30	---			
MT 30	0.011	0.009	1.64	G	0.002	0.002	
NE 31	-0.022	-0.131	5.08	G	0.109	0.109	
OK 40	0.064	0.030	3.13	?	0.034		
TX 48	0.100	-0.024	3.63	P	0.124		0.124
VA 51	-0.027	0.018	3.62	X			
WI 55	0.155	0.184	2.40	?	-0.029		
Mean difference					0.088	0.149	0.077
n					28	11	9
S_D					0.148	0.158	0.125
$t_{\text{alpha/2, n-1}}$					2.546	2.862	3.007
Confidence interval lower limit					0.016	0.013	-0.048
Confidence interval upper limit					0.159	0.285	0.202
Significant difference? (Overall confidence level = 95%)					yes	yes	no

[1] G = Drainage function rated as good.
[2] P = Drainage function rated as poor.
[3] ? = Drainage outlets not found.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] --- = lacking measurement data for one or both test sections.

TABLE 14 Change in International Roughness Index (IRI) in SPS-1 undrained asphalt-treated base (ATB) sections versus drained permeable asphalt-treated base (ATB/PATB) sections

	IRI		Age, years	Drainage functioning	Difference		
	ATB	**ATB/PATB**					
Drained	N	Y			All	Good	Poor
Site	**0103**	**0107**					
AL 01	0.033	0.306	5.18	G[1]	-0.273	-0.273	
DE 10	0.009	0.093	3.49	G	-0.084	-0.084	
FL 12	0.009	-0.004	3.62	P[12]	0.013		0.013
IA 19	0.544	---[3]	6.29	X[4]			
KS 20	0.619	0.152	4.27	?[5]	0.467		
NV 32	-0.001	-0.028	3.14	P	0.027		0.027
NM 35	0.244	0.215	4.15	P	0.029		0.029
OH 39	1.729	0.164	0.37	X			
Site	**0104**	**0108**					
AL 01	0.054	-0.028	3.72	G	0.082	0.082	
DE 10	-0.041	-0.041	3.49	G	0.000	0.000	
FL 12	-0.012	-0.146	3.62	?	0.134		
IA 19	0.466	0.953	6.29	X			
KS 20	0.271	0.781	7.00	P	-0.510		-0.510
NV 32	-0.026	-0.030	3.14	P	0.004		0.004
NM 35	0.156	0.022	4.15	P	0.134		0.134
OH 39	0.571	1.087	4.01	X			
Site	**0115**	**0119**					
AZ 04	0.030	0.126	6.89	G	-0.096	-0.096	
AR 05	0.156	0.813	5.54	P	-0.657		-0.657
LA 22	---	---	---	---			
MI 26	0.141	---	3.30	---			
MT 30	0.023	-0.020	1.64	G	0.043	0.043	
NE 31	---	-0.219	5.08	---			
OK 40	0.032	-0.007	3.13	?	0.039		
TX 48	0.328	0.489	3.63	P	-0.161		-0.161
VA 51	0.001	0.058	3.62	X			
WI 55	0.284	0.101	2.40	?	0.183		
Site	**0116**	**0120**					
AZ 04	0.064	0.141	6.89	G	-0.077	-0.077	
AR 05	0.024	0.657	5.54	P	-0.633		-0.633
LA 22	---	---	---	---			
MI 26	0.104	0.150	3.30	?	-0.046		
MT 30	-0.005	0.051	1.64	G	-0.056	-0.056	
NE 31	-0.104	-0.168	5.08	G	0.064	0.064	
OK 40	-0.018	0.044	3.13	?	-0.062		
TX 48	0.521	0.099	3.63	P	0.422		0.422
VA 51	0.004	0.009	3.62	X			
WI 55	0.226	0.012	2.40	?	0.214		
Mean difference					-0.031	-0.044	-0.133
N					26	9	10
S_D					0.263	0.109	0.356
$t_{alpha/2, n-1}$					2.560	3.007	2.925
Confidence interval lower limit					-0.163	-0.153	-0.462
Confidence interval upper limit					0.101	0.065	0.196
Significant difference (Overall confidence level = 95%)					no	no	no

[1] G = Drainage function rated as good.
[2] P = Drainage function rated as poor.
[3] --- = lacking measurement data for one or both test sections.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] ? = Drainage outlets not found.

TABLE 15 Change in International Roughness Index (IRI) in SPS-1 undrained asphalt-treated base over dense-graded aggregate (ATB/AGG) sections versus drained permeable asphalt-treated base over aggregate (PATB/AGG) sections

	IRI		Age, years	Drainage functioning	Difference		
	ATB/AGG	PATB/AGG					
Drained	**N**	**Y**			**All**	**Good**	**Poor**
Site	**0105**	**0107**					
AL 01	0.023	0.306	5.18	G[1]	-0.283	-0.283	
DE 10	0.040	0.093	3.49	G	-0.053	-0.053	
FL 12	0.007	-0.004	3.62	P[2]	0.011		0.011
IA 19	0.538	---[3]	6.29	X[4]			
KS 20	1.167	0.152	4.27	?[5]	1.015		
NV 32	-0.026	-0.028	3.14	P	0.002		0.002
NM 35	0.133	0.215	4.15	P	-0.082		-0.082
OH 39	0.688	0.164	0.37	G	0.524	0.524	
Site	**0106**	**0108**					
AL 01	0.107	-0.017	5.18	G	0.124	0.124	
DE 10	-0.034	-0.041	3.49	G	0.007	0.007	
FL 12	-0.011	-0.146	3.62	?	0.135		
IA 19	0.357	0.953	6.29	X			
KS 20	0.771	0.781	7.00	P	-0.010		-0.010
NV 32	-0.010	-0.030	3.14	P	0.020		0.020
NM 35	0.269	0.022	4.15	P	0.247		0.247
OH 39	0.646	1.087	4.01	X			
Site	**0117**	**0119**					
AZ 04	0.001	0.126	6.89	G	-0.125	-0.125	
AR 05	0.126	0.813	5.54	P	-0.687		-0.687
LA 22	---	---	---	---			
MI 26	0.546	---	3.30	---			
MT 30	-0.014	-0.020	1.64	G	0.006	0.006	
NE 31	-0.109	-0.219	5.08	G	0.110	0.110	
OK 40	0.048	-0.007	3.13	?	0.055		
TX 48	0.036	0.489	3.63	P	-0.453		-0.453
VA 51	0.002	0.058	3.62	?	-0.056		
WI 55	0.166	0.101	2.40	?	0.065		
Site	**0118**	**0120**					
AZ 04	0.055	0.141	6.89	G	-0.086	-0.086	
AR 05	0.112	0.657	5.54	P	-0.545		-0.545
LA 22	---	---	---	---			
MI 26	0.279	0.150	3.30	X			
MT 30	0.019	0.051	1.64	G	-0.032	-0.032	
NE 31	-0.163	-0.168	5.08	G	0.005	0.005	
OK 40	0.082	0.044	3.13	?	0.038		
TX 48	0.038	0.099	3.63	P	-0.061		-0.061
VA 51	0.047	0.009	3.62	G	0.038	0.038	
WI 55	0.150	0.012	2.40	?	0.138		
Mean difference					0.002	0.020	-0.156
N					29	12	10
S_D					0.301	0.192	0.299
$t_{\text{alpha/2, n-1}}$					2.540	2.812	2.925
Confidence interval lower limit					-0.140	-0.136	-0.432
Confidence interval upper limit					0.144	0.176	0.121
Significant difference (Overall confidence level = 95%)					no	no	no

[1] G = Drainage function rated as good.
[2] P = Drainage function rated as poor.
[3] --- = lacking measurement data for one or both test sections.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] ? = Drainage outlets not found.

TABLE 16 Change in rutting in SPS-1 undrained dense-graded aggregate (AGG) sections versus drained asphalt-treated base over permeable asphalt-treated base (ATB/PATB) sections

	IRI		Age, years	Drainage functioning	Difference		
	AGG	ATB/PATB					
Drained	N	Y			All	Good	Poor
Site	**0101**	**0110**					
AL 01	2	-1	6.11	G[1]	3	3	
DE 10	---[2]	2	3.68	---			
FL 12	---	---	---	---			
IA 19	0	-1	4.88	?[3]	1		
KS 20	-5	3	6.36	?	-8		
NV 32	0	2	4.35	P[4]	-2		-2
NM 35	3	1	3.01	P	2		2
OH 39	--	1	3.73	X[5]			
Site	**0102**	**0111**					
AL 01	8	3	6.11	G	5	5	
DE 10	7	1	3.68	G	6	6	
FL 12	---	---	---	---			
IA 19	7	-1	4.88	X			
KS 20	-11	-1	6.36	?	-10		
NV 32	5	2	4.35	P	3		3
NM 35	1	1	3.01	P	0		0
OH 39	---	2	3.73	X			
Site	**0113**	**0122**					
AZ 04	2	7	4.79	G	-5	-5	
AR 05	-4	-1	4.56	P	-3		-3
LA 22	3	1	1.51	?	2		
MI 26	---	---	---	---			
MT 30	1	2	1.08	G	-1	-1	
NE 31	23	9	4.26	G	14	14	
OK 40	2	0	0.96	?	2		
TX 48	1	1	2.17	P	0		0
VA 51	4	0	2.14	G	4	4	
WI 55	5	-24	2.13	?	29		
Site	**0114**	**0123**					
AZ 04	4	-3	3.88	G	7	7	
AR 05	1	0	4.56	P	1		1
LA 22	4	2	1.51	?	2		
MI 26	---	2	4.18	---			
MT 30	1	0	1.08	G	1	1	
NE 31	20	17	4.26	G	3	3	
OK 40	1	1	0.96	?	0		
TX 48	7	2	2.17	P	5		5
VA 51	0	3	2.14	X			
WI 55	5	5	2.13	?	0		
Mean difference					2.3	3.7	0.8
N					27	10	8
S_D					7.1	5.1	2.6
$t_{\text{alpha/2, n-1}}$					2.553	2.925	3.118
Confidence interval lower limit					-1.2	-1.0	-2.1
Confidence interval upper limit					5.7	8.4	3.6
Significant difference (Overall confidence level = 95%)					no	no	no

[1] G = Drainage function rated as good.
[2] --- = lacking measurement data for one or both test sections.
[3] ? = Drainage outlets not found.
[4] P = Drainage function rated as poor.
[5] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.

TABLE 17 Change in rutting in SPS-1 undrained asphalt-treated base (ATB) sections versus drained permeable asphalt-treated base over aggregate (PATB/AGG) sections

Base Type	ATB	PATB/AGG	Age, years	D Drainage functioning	ifference		
Drained	N	Y			All	Good	Poor
Site	**0103**	**0107**					
AL 01	3	7	6.11	G[1]	-4	-4	
DE 10	3	2	3.68	G	1	1	
FL 12	---	---[2]	---	---			
IA 19	-2	---	4.88	X[3]			
KS 20	3	-8	6.36	?[4]	11		
NV 32	2	0	4.35	P[5]	2		2
NM 35	2	2	3.01	P	0		0
OH 39	12	---	3.73	X			
Site	**0104**	**0108**					
AL 01	4	2	6.11	G	2	2	
DE 10	3	2	3.68	G	1	1	
FL 12	---	---	---	---			
IA 19	2	4	5.43	X			
KS 20	0	3	6.36	P	-3		-3
NV 32	1	2	4.35	P	-1		-1
NM 35	1	1	3.01	P	0		0
OH 39	5	14	3.73	X			
Site	**0115**	**0119**					
AZ 04	1	8	4.79	G	-7	-7	
AR 05	3	-1	4.56	P	4		4
LA 22	5	2	1.51	G	3	3	
MI 26	5	---	3.30	---			
MT 30	0	0	1.08	G	0	0	
NE 31	11	6	4.26	G	5	5	
OK 40	0	0	0.96	?	0		
TX 48	8	1	2.17	P	7		7
VA 51	0	2	2.14	X			
WI 55	7	7	2.13	?	0		
Site	**0116**	**0120**					
AZ 04	3	5	4.79	G	-2	-2	
AR 05	0	-1	4.56	P	1		1
LA 22	4	-3	1.51	G	7	7	
MI 26	2	---	4.18	---			
MT 30	0	1	1.08	G	-1	-1	
NE 31	10	8	4.26	G	2	2	
OK 40	0	0	0.96	?	0		
TX 48	10	2	2.17	P	8		8
VA 51	1	3	2.14	X			
WI 55	5	2	2.13	?	3		
Mean difference					1.5	0.6	2.0
N					26	12	9
S_D					3.9	3.8	3.7
$t_{alpha/2, n-1}$					2.560	2.812	3.007
Confidence interval lower limit					-0.5	-2.5	-1.7
Confidence interval upper limit					3.5	3.7	5.7
Significant difference (Overall confidence level = 95%)					no	no	no

[1] G = Drainage function rated as good.
[2] --- = lacking measurement data for one or both test sections.
[3] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[4] ? = Drainage outlets not found.
[5] P = Drainage function rated as poor.

TABLE 18 Change in rutting in SPS-1 undrained asphalt-treated base over dense-graded aggregate (ATB/AGG) sections versus drained permeable asphalt-treated base over aggregate (PATB/AGG) sections

Base Type	ATB/AGG	PATB/AGG	Age, years	Drainage functioning	Difference		
Drained	N	Y			All	Good	Poor
Site	**0105**	**0107**					
AL 01	4	7	6.11	G[1]	-3	-3	
DE 10	5	2	3.68	G	3	3	
FL 12	---[2]	---	---	---			
IA 19	2	---	4.88	X[3]			
KS 20	21	-8	6.36	?[4]	29		
NV 32	3	0	4.35	P[5]	3		3
NM 35	1	2	3.01	P	-1		-1
OH 39	5	---	1.12	---			
Site	**0106**	**0108**					
AL 01	1	2	6.11	G	-1	-1	
DE 10	1	2	3.68	G	-1	-1	
FL 12	---	---	---	---			
IA 19	1	4	5.43	X			
KS 20	1	3	6.36	P	-2		-2
NV 32	0	2	4.35	P	-2		-2
NM 35	-3	1	0.58	P	-4		-4
OH 39	2	14	3.73	X			
Site	**0117**	**0119**					
AZ 04	3	8	4.79	G	-5	-5	
AR 05	2	-1	4.56	P	3		3
LA 22	5	2	1.51	G	3	3	
MI 26	5	---	4.18	---			
MT 30	0	0	1.08	G	0	0	
NE 31	11	6	4.26	G	5	5	
OK 40	2	0	0.96	?	2		
TX 48	0	1	2.17	P	-1		-1
VA 51	1	2	2.14	?	-1		
WI 55	5	7	2.13	?	-2		
Site	**0118**	**0120**					
AZ 04	2	5	4.79	G	-3	-3	
AR 05	-1	-1	4.56	P	0		0
LA 22	4	-3	1.51	G	7	7	
MI 26	---	---	---	X			
MT 30	2	1	1.08	G	1	1	
NE 31	13	8	4.26	G	5	5	
OK 40	1	0	0.96	?	1		
TX 48	1	2	2.17	P	-1		-1
VA 51	3	3	2.14	G	0	0	
WI 55	7	2	2.13	?	5		
Mean difference					1.4	0.8	-0.6
N					28	13	9
S_D					6.2	3.6	2.3
$t_{\text{alpha/2, n-1}}$					2.546	2.772	3.007
Confidence interval lower limit					-1.5	-1.9	-2.9
Confidence interval upper limit					4.4	3.6	1.7
Significant difference (Overall confidence level = 95%)					no	no	no

[1] G = Drainage function rated as good.

[2] --- = lacking measurement data for one or both test sections.

[3] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.

[4] ? = Drainage outlets not found.

[5] P = Drainage function rated as poor.

TABLE 19 Change in cracking in meters in SPS-1 undrained dense-graded aggregate (AGG) sections versus drained asphalt-treated base over permeable asphalt-treated base (ATB/PATB) sections

Base Type	AGG	ATB/PATB	Age, years	Drainage functioning	Difference		
Drained	N	Y			All	Good	Poor
Site	**0101**	**0110**					
AL 01	8	9	7.21	G[1]	-1	-1	
DE 10	0	0	4.50	G	0	0	
FL 12	---[2]	---	---	---			
IA 19	19	12	7.70	?[3]	7		
KS 20	0	5	3.40	?	-5		
NV 32	2	1	5.63	P[4]	1		1
NM 35	---	---	---	---			
OH 39	0	0	1.01	X[5]			
Site	**0102**	**0111**					
AL 01	18	13	7.21	G	5	5	
DE 10	15	0	4.50	G	15	15	
FL 12	---	---	---	---			
IA 19	32	22	7.70	X			
KS 20	0	22	3.40	?	-22		
NV 32	1	0	5.63	P	1		1
NM 35	---	---	---	---			
OH 39	---	23	5.44	X			
Site	**0113**	**0122**					
AZ 04	12	7	7.75	G	5	5	
AR 05	15	13	5.82	P	2		2
LA 22	---	---	---	---			
MI 26	---	---	---	---			
MT 30	13	16	1.78	G	-3	-3	
NE 31	---	---	---	---			
OK 40	---	---	---	---			
TX 48	4	2	3.89	P	2		2
VA 51	0	0	1.44	G	0	0	
WI 55	---	---	---	---			
Site	**0114**	**0123**					
AZ 04	13	16	7.75	G	-3	-3	
AR 05	14	13	5.82	P	1		1
LA 22	---	---	---	---			
MI 26	---	4	4.87	---			
MT 30	13	13	1.78	G	0	0	
NE 31	---	---	---	---			
OK 40	---	---	---	---			
TX 48	0	0	3.89	P	0		0
VA 51	0	0	1.44	X			
WI 55	---	---	---	---			
Mean difference					0.3	2.0	1.2
N					18	9	6
S_D					7.1	5.7	0.8
$t_{alpha/2, n-1}$					2.648	3.007	3.521
Confidence interval lower limit					-4.2	-3.7	0.1
Confidence interval upper limit					4.7	7.7	2.2
Significant difference (Overall confidence level = 95%)					no	no	yes

[1] G = Drainage function rated as good.
[2] --- = lacking measurement data for one or both test sections.
[3] ? = Drainage outlets not found.
[4] P = Drainage function rated as poor.
[5] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.

TABLE 20 Change in cracking in meters in SPS-1 undrained asphalt-treated base (ATB) sections versus drained permeable asphalt-treated base over aggregate (PATB/AGG) sections

Base Type	ATB	PATB/AGG	Age, years	Drainage functioning	Difference		
Drained	N	Y			All	Good	Poor
Site	**0103**	**0107**					
AL 01	11	9	7.21	G[1]	2	2	
DE 10	0	0	4.50	G	0	0	
FL 12	---[2]	---	---	---			
IA 19	11	16	7.70	X[3]			
KS 20	18	0	3.40	?[4]	18		
NV 32	3	0	5.63	P[5]	3		3
NM 35	---	---	---	---			
OH 39	42	---	5.44	X			
Site	**0104**	**0108**					
AL 01	0	21	7.21	G	-21	-21	
DE 10	0	0	4.50	G	0	0	
FL 12	---	---	---	---			
IA 19	23	17	7.70	X			
KS 20	31	60	6.10	P	-29		-29
NV 32	1	1	5.63	P	0		0
NM 35	---	---	---	---			
OH 39	24	46	5.44	X			
Site	**0115**	**0119**					
AZ 04	9	9	7.75	G	0	0	
AR 05	14	28	5.82	P	-14		-14
LA 22	---	---	---	---			
MI 26	12	---	4.87	---			
MT 30	12	14	1.78	G	-2	-2	
NE 31	---	---	---	---			
OK 40	---	---	---	---			
TX 48	0	0	3.89	P	0		0
VA 51	0	0	1.44	X			
WI 55	---	---	---	---			
Site	**0116**	**0120**					
AZ 04	5	10	7.75	G	-5	-5	
AR 05	13	20	5.82	P	-7		-7
LA 22	---	---	---	---			
MI 26	0	4	0.93	?	-4		
MT 30	12	21	1.78	G	-9	-9	
NE 31	---	---	---	---			
OK 40	---	---	---	---			
TX 48	0	0	3.89	P	0		0
VA 51	0	0	1.44	X			
WI 55	---	---	---	---			
Mean difference					-4.0	-4.4	-6.7
N					17	8	7
S_D					10.4	7.6	11.4
$t_{alpha/2, n-1}$					2.666	3.118	3.276
Confidence interval lower limit					-10.7	-12.7	-20.8
Confidence interval upper limit					2.7	4.0	7.4
Significant difference (Overall confidence level = 95%)					no	no	no

[1] G = Drainage function rated as good.
[2] --- = lacking measurement data for one or both test sections.
[3] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[3] ? = Drainage outlets not found.
[5] P = Drainage function rated as poor.

TABLE 21 Change in cracking in meters in SPS-1 undrained asphalt-treated base over dense-graded aggregate (ATB/AGG) sections versus drained permeable asphalt-treated base over aggregate (PATB/AGG) sections

Base Type	ATB/AGG	ATB/PATB	Age, years	Drainage functioning	Difference		
Drained	**N**	**Y**			**All**	**Good**	**Poor**
Site	**0105**	**0107**					
AL 01	25	9	7.21	G[1]	16	16	
DE 10	0	0	4.50	G	0	0	
FL 12	---[2]	---	---	---			
IA 19	27	16	7.70	X[3]			
KS 20	30	0	3.40	?[4]	30		
NV 32	2	0	5.63	P[5]	2		2
NM 35	---	---	---	---			
OH 39	0	---	2.13	---			
Site	**0106**	**0108**					
AL 01	4	21	7.21	G	-17	-17	
DE 10	0	0	4.50	G	0	0	
FL 12	---	---	---	---			
IA 19	17	17	7.70	X			
KS 20	23	60	6.10	P	-37		-37
NV 32	0	1	5.63	P	-1		-1
NM 35	---	---	---	---			
OH 39	32	46	5.44	X			
Site	**0117**	**0119**					
AZ 04	5	9	7.75	G	-4	-4	
AR 05	13	28	5.82	P	-15		-15
LA 22	---	---	---	---			
MI 26	5	---	4.87	---			
MT 30	14	14	1.78	G	0	0	
NE 31	---	---	---	---			
OK 40	---	---	---	---			
TX 48	3	0	3.89	P	3		3
VA 51	0	0	1.44	?	0		
WI 55	---	---	---	---			
Site	**0118**	**0120**					
AZ 04	9	10	7.75	G	-1	-1	
AR 05	14	20	5.82	P	-6		-6
LA 22	---	---	---	---			
MI 26	0	4	0.93	X			
MT 30	12	21	1.78	G	-9	-9	
NE 31	---	---	---	---			
OK 40	---	---	---	---			
TX 48	13	0	3.89	P	13		13
VA 51	0	0	1.44	G	0	0	
WI 55	---	---	---	---			
Mean difference					-1.4	-1.7	-5.9
N					18	9	7
S_D					14.0	8.8	16.2
$t_{\text{alpha/2, n-1}}$					2.648	3.007	3.276
Confidence interval lower limit					-10.2	-10.5	-25.9
Confidence interval upper limit					7.3	7.1	14.2
Significant difference (Overall confidence level = 95%)					no	no	no

[1] G = Drainage function rated as good.
[2] --- = lacking measurement data for one or both test sections.
[3] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[3] ? = Drainage outlets not found.
[5] P = Drainage function rated as poor.

Table 18 shows the comparisons of undrained dense asphalt-treated base over dense-graded aggregate (ATB/AGG) versus drained permeable asphalt-treated base over aggregate (PATB/AGG). For drained PATB/AGG sections with drainage functioning rated as good, the change in rutting was slightly, but not significantly, less than in the corresponding undrained ATB/AGG sections. The same was true for all drained PATB/AGG sections considered together, regardless of drainage functioning. For drained PATB/AGG sections with drainage functioning rated as poor, the change in rutting was slightly but not significantly greater than in the corresponding undrained ATB/AGG sections.

Effect of Drainage on Asphalt Pavement Cracking Development

For the purpose of this analysis, the area of alligator cracking (all severities) was added to the area affected by longitudinal cracking (sealed and unsealed, all severities, wheelpath and nonwheelpath, length times 18 inches or 0.45 m), and this area was divided by the area of the pavement section (typically 556 m^2). Both alligator cracking and longitudinal cracking were considered together, because examination of the survey data indicated that the trends in each may be very erratic from year to year whereas the sum of the two tends to have a more stable trend. This is believed to be due to variation from year to year in the survey technicians' classification of the distress observed.

It is conceivable that this summation method produces some overestimates of the percent area cracked in cases when both alligator cracking and longitudinal cracking are located in the same area. Also, the selection of 18 inches as a typical wheelpath width is arbitrary, and different cracked area percentages would be obtained if some other width were assumed.

The cracking histories for eleven SPS-1 sites are shown in Appendix A. Cracking histories are not shown for the Florida, Louisiana, Nebraska, Nevada, New Mexico, Oklahoma, and Wisconsin sites because of very low calculated cracking levels.

The comparisons of cracking between drained and undrained sections of matching designs are shown in Tables 19, 20, and 21. Which comparisons were deemed possible was assessed on the basis of the drainage detection and drainage functioning information summarized in Tables 11 and 12.

Table 19 shows the comparisons of undrained dense-graded aggregate base (AGG) versus dense asphalt-treated base over drained permeable asphalt-treated base (ATB/PATB). For drained ATB/PATB sections with drainage functioning subjectively rated as good, cracking was slightly, but not significantly, less than in the undrained AGG sections of corresponding design. The same was true for drained ATB/PATB sections with drainage functioning rated as poor and for all drained ATB/PATB sections combined (good, poor, and unknown drainage functioning).

Table 20 shows the comparisons of undrained dense asphalt-treated base (ATB) versus drained permeable asphalt-treated base over aggregate (PATB/AGG). For drained PATB/AGG sections with drainage functioning rated as good, cracking was slightly, but not significantly, greater than in the corresponding undrained ATB sections. The same was true for drained PATB/AGG sections with drainage functioning rated as poor, and for all drained PATB/AGG sections combined, regardless of drainage functioning.

Table 21 shows the comparisons of undrained dense asphalt-treated base over dense-graded aggregate (ATB/AGG) versus drained permeable asphalt-treated base over aggregate (PATB/AGG). For drained PATB/AGG sections with drainage functioning rated as good, cracking was slightly, but not significantly, greater than in the corresponding undrained ATB/AGG sections. The same was true for drained PATB/AGG sections with drainage functioning rated as poor, and for all drained PATB/AGG sections considered together, regardless of drainage functioning.

CHAPTER 3

EFFECTS OF SUBSURFACE DRAINAGE ON CONCRETE PAVEMENTS

DESCRIPTION OF LTPP EXPERIMENT SPS-2

The SPS-2 experiment (Strategic Study of Structural Factors for Rigid Pavements) was designed to assess the influence of the following factors on the performance of jointed concrete pavements:

- Concrete thickness,
- Concrete flexural strength,
- Base type,
- Lane width,
- Subdrainage,
- Climate,
- Subgrade, and
- Truck traffic level.

The Strategic Highway Research Program's original experimental design and research plan for SPS-2 are described in Reference 5. The design factorial for the SPS-2 experiment is shown in Table 22. The first two digits (02) of the number shown within each cell signify the SPS-2 experiment, and the last two digits signify the test section design.

The base types listed in Table 22 are dense-graded aggregate, lean concrete base, and permeable asphalt treated.

Other than some thickness deviations, the pavement structures actually constructed conform to the experiment design shown in Table 22, with one important exception: which sections are drained and which are not. The field inspection of the drains, discussed in more detail later in this chapter, found several instances of the following discrepancies:

- Some pavement sections were found to have drains installed even though they should not, according to the experiment design;
- Some pavement sections should have had drains installed, but the presence of the drains was not confirmed in the field inspections; and
- Some pavement sections should and do have drains installed, but the drains do not appear to be functioning effectively.

The site factorial for the SPS-2 experiment is shown in Table 23. Note that although two or more states built the same designs in a few cases, these are not replicates in the true sense of the word, as the sites are not identical in terms of the concomitant variable, truck traffic level, nor are their climates identical. The California SPS-2 project was opened to traffic in October 2000, and little information about it was available in the database as of June 2001. The western LTPP regional center reports that the soil is coarse (silty sand).

The states listed in the upper row for each subgrade type in Table 23 are those that built designs 0201 through 0212. The pavement designs in the core SPS-2 experiment constructed at these sites are shown in Table 24. The states listed in the lower row for each subgrade type in Table 23 are those that built designs 0213 through 0224. These pavement designs are shown in Table 25.

The geographic distribution of the fourteen SPS-2 sites is illustrated in Figure 5. Location data for the SPS-2 projects are given in Table 26.

Climate Characterization

The climatic distribution of the SPS-2 sites was determined by extracting the latitude and longitude for each site from the LTPP database, searching the National Oceanic and Atmospheric Administration (NOAA) database for the weather station nearest the SPS-2 site, extracting the 30-year average monthly precipitation levels and average monthly temperatures for the weather station, and calculating the average annual precipitation and average annual temperature for each. These data are provided in Table 27. The distribution of the SPS-2 sites with respect to average annual precipitation and temperature are illustrated in Figure 6.

The need for subsurface drainage can be quantified with respect to a design rainfall, that is, one of a given magnitude, duration, and frequency. For example, a 1-year, 1-hour rainfall is an amount of rainfall that at a particular location lasts 1 hour and occurs, on average, once a year. Rainfall frequency information is not easily accessed in tabular form but rather must be obtained from contour maps. The 1-year, 1-hour rainfalls for the SPS-1 and SPS-2 sites were determined from contour maps in Reference 2.

In the absence of rainfall frequency information, it is possible to estimate the 1-year, 1-hour rainfall as a function of the average annual precipitation, which is more readily known. As was shown in Figure 3, there is an evident (although nonlinear) correlation between average annual precipitation

TABLE 22 SPS-2 design factorial

			Undrained		Drained
Slab thickness, inches	Flexural strength, psi	Lane width, ft	Dense-graded aggregate base	Lean concrete base	Permeable asphalt-treated base
8	550	12	0201	0205	0209
		14	0213	0217	0221
	900	12	0214	0218	0222
		14	0202	0206	0210
11	550	12	0215	0219	0223
		14	0203	0207	0211
	900	12	0204	0208	0212
		14	0216	0220	0224

TABLE 23 SPS-2 site factorial

	Wet		Dry	
	Freeze	Nonfreeze	Freeze	Nonfreeze
Fine subgrade	OH, KS	NC		
	MI, IA, ND	AR		
Coarse subgrade	DE		NV, WA	CA
	WI		CO	AZ

TABLE 24 Core SPS-2 test sections built at California, Delaware, Kansas, Nevada, North Carolina, Ohio, and Washington sites

			Undrained		Drained
Slab thickness, inches	Flexural strength, psi	Lane width, ft	Dense-graded aggregate base	Lean concrete base	Permeable asphalt-treated base
8	550	12	0201	0205	0209
		14			
	900	12			
		14	0202	0206	0210
11	550	12			
		14	0203	0207	0211
	900	12	0204	0208	0212
		14			

and the 1-year, 1-hour rainfall for nearly all of the SPS-1 and SPS-2 sites. The exceptions are the three SPS-1 sites closest to the Gulf coast (Texas, Louisiana, and Florida), for which the correlation curve seems to be shifted upward—that is, higher 1-year, 1-hour rainfall at those sites than for noncoastal sites with similar levels of average annual precipitation.

Test Section Layouts and Pavement Structures

The station limits, layer thicknesses, and material types for each of the SPS-2 test sections were extracted from the SPS_PROJECT_STATIONS and TST_L05B data tables in the LTPP database. The thicknesses in the TST_L05B table represent the LTPP regional data collection centers' best estimates of the as-constructed layer thicknesses and materials. (The test section layout and pavement layer data are given in Appendix B. For the California site, as-constructed layer thickness estimates are not yet known, so the design layer thicknesses are shown.) The layout diagrams also indicate which sections are supposed to be drained and which are not and the locations of edgedrain outlets inspected in the field inspections conducted in late 2001 and early 2002.

TABLE 25 Core SPS-2 test sections built at Arizona, Arkansas, Colorado, Iowa, Michigan, North Dakota, and Wisconsin sites

			Undrained		Drained
Slab thickness, inches	Flexural strength, psi	Lane width, ft	Dense-graded aggregate base	Lean concrete base	Permeable asphalt treated base
8	550	12			
		14	0213	0217	0221
	900	12	0214	0218	0222
		14			
11	550	12	0215	0219	0223
		14			
	900	12			
		14	0216	0220	0224

The presence of filter fabric below the permeable asphalt-treated base in the SPS-2 test sections designed to be drained is summarized in Table 28. This summary is based on information in the TST_L05B and SPS2_LAYER data tables and the LTPP regional support centers' responses to an LTPP Data Analysis/Operations Feedback Report (KTH-2, 11 June 2002) submitted by the NCHRP 1-34C research team.

In nearly all cases, no filter fabric was used below the permeable asphalt-treated base in the SPS-2 test sections designed to be drained. The exceptions are the four Arkansas SPS-2 sections and the four Iowa SPS-2 test sections with this base type. The four Arkansas sections have a geotextile below the PATB, according to the regional support center, although this is not reflected in the national LTPP database as of release 12.0.

Traffic Characterization

The 18-kip-equivalent single-axle (ESAL) levels at the SPS-2 sites were determined by extracting the following data from the LTPP database:

- ESAL estimates obtained from traffic monitoring during the experiment from the TRF_MON_EST_ESAL data table; and
- Axle load distributions obtained from traffic monitoring during the experiment from the TRF_MONITOR_AXLE_DISTRIBUTION data table.

Axle load distribution data were available for eleven of the fourteen SPS-2 sites. Data were not available for the sites in California, North Dakota, and Wisconsin.

ESALs were calculated for the years in which axle load distribution data were available, using (1) the number of axles reported in each load range in the distribution and (2) load equivalency factors calculated as a function of the as-constructed concrete slab thickness. For years during the experiment in which axle load distribution data were not available, ESAL estimates from TRF_MON_ EST_ESAL table were used if available.

In a few cases, linear interpolations of annual ESALs were necessary for years in which no axle load distribution or ESAL data were available. It was also necessary in a few cases to extrapolate a year or two before or after the years for which data were available. A growth rate of 5 percent was used for these extrapolations.

From the annual ESAL estimates for the different test sections at each site, the average annual ESALs for the site were calculated. The average annual ESALs estimates for each site were used to calculate accumulated ESAL estimates from the date of opening to traffic to several dates of profile, faulting, and cracking measurements. The measurement dates were those on which measurements were obtained for most or all of the test sections at the site. When more than one such date occurred in the same year for a particular type of measurement, one of the dates was selected for use. The annual and accumulated ESAL estimates for each site with data available are provided in Appendix B.

The age of each SPS-2 site and the accumulated rigid pavement ESALs for each site with traffic data available, as of the latest date of condition measurements available for this study, are shown in Table 29. Also shown is the accumulated ESALs divided by the age, which gives a rough estimate of the average annual ESAL level during the time that each site has been in service.

The ages and accumulated ESALs at the SPS-2 sites are also illustrated in Figure 7. The vertical scale of this graph was chosen to be compatible with the range of flexible pavement ESALs for the SPS-1 sites (shown in Chapter 2). Taking into consideration the fact that one flexible pavement ESAL is roughly equivalent to 1.5 rigid pavement ESALs, it is nonetheless clear that the SPS-2 sites have, on average,

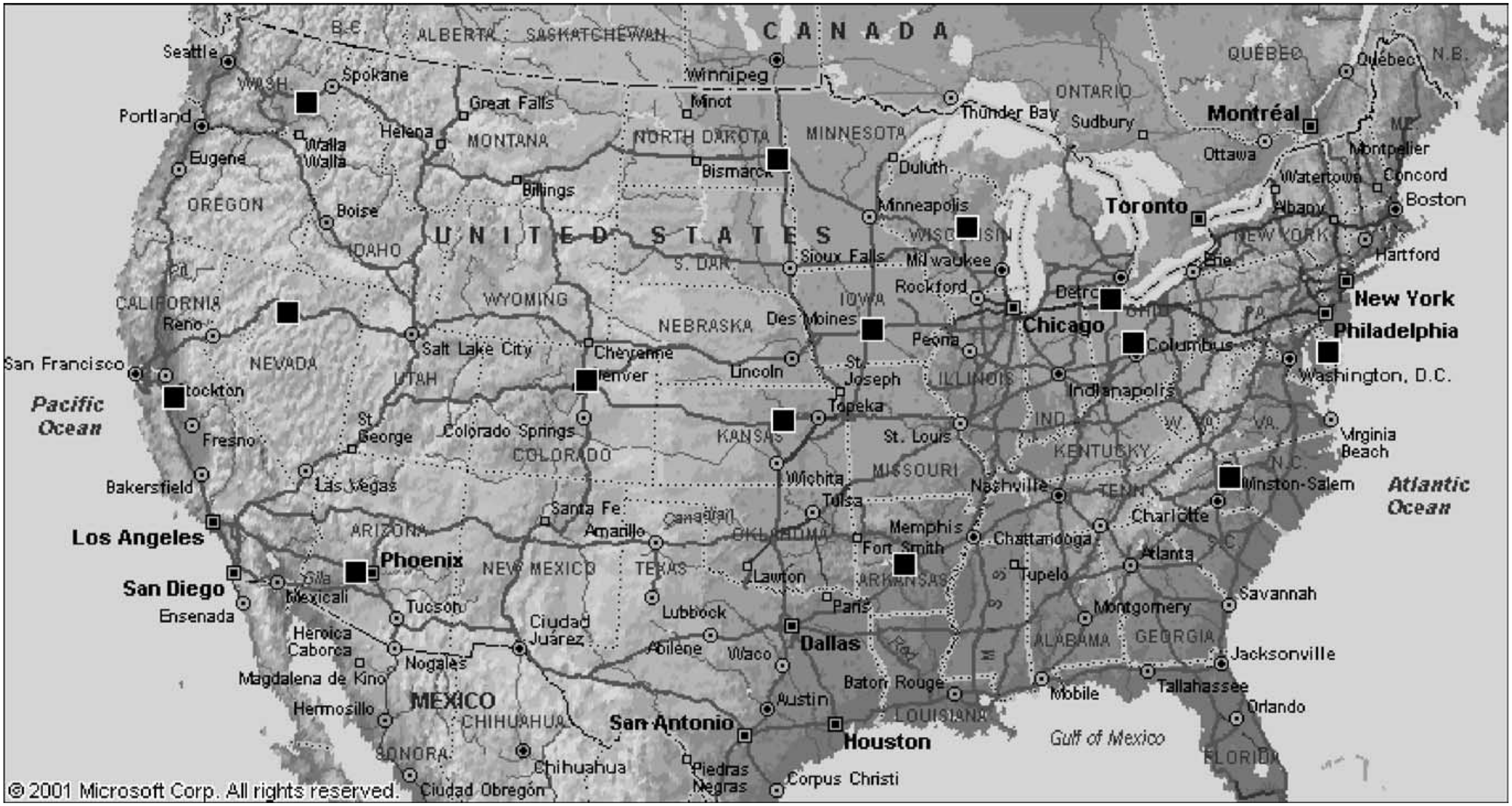

Figure 5. SPS-2 sites.

TABLE 26 SPS-2 location data

SHRP ID	State	County	Nearby city or town	Route	Latitude	Longitude
040200	AZ	Maricopa	Phoenix	I-10	33.45	112.74
050200	AR	Saline	Benton	I-30	34.54	92.68
060200	CA*	Merced	Turlock	SR 99	37.42	120.77
080200	CO	Adams	Denver	I-76	39.97	104.79
100200	DE	Sussex	Ellendale	US 113	38.87	75.44
190200	IA	Polk	Des Moines	US 65	41.65	93.47
200200	KS	Dickenson	Salina	I-70	38.97	97.09
260200	MI	Monroe	Toledo, Ohio	US 23	41.75	83.70
320200	NV	Lander	Battle Mountain	I-80	40.72	117.04
370200	NC	Davidson	Lexington	US 52	35.87	80.27
380200	ND	Cass	Fargo	I-94	46.88	97.17
390200	OH	Delaware	Delaware	US 23	40.38	83.06
530200	WA	Adams	Ritzville	US 395	47.06	118.42
550200	WI	Marathon	Wausau	SR 29	44.49	89.23

* Route, county, and nearby town based on location indicated by latitude and longitude data.

received more than double the ESALs that the SPS-1 sites have received.

SPS-2 Construction

Some information on construction of the SPS-2 sites is available in the construction reports prepared by the LTPP regional support centers. Construction deviation reports were obtained for seven of the fourteen SPS-2 sites: Arizona, Arkansas, Colorado, Delaware, Nevada, North Carolina, and Washington. The information available on construction deviations is summarized in Table 30.

FIELD INSPECTIONS OF DRAINS AT SPS-2 SITES

Video inspections of the longitudinal subdrains and outlets at the SPS-2 sites were conducted in late 2001 and early 2002, under an FHWA contract with NCHRP support, using the same procedure as that used at the SPS-1 sites (described

TABLE 27 Average annual precipitation and temperature levels for weather stations nearest SPS-2 sites

SPS-2 Site				Nearest Weather Station					
State	State Code	Latitude (degrees)	Longitude (degrees)	ID	Name	Latitude (degrees)	Longitude (degrees)	Average Annual Precipitation (inches)	Average Annual Temperature (degrees F)
AZ	04	33.45	112.74	029287	Wickenburg	33.59	112.44	12.20	66.10
AR	05	34.54	92.68	030130	Alum Fork	34.48	92.52	53.68	61.70
CA	06	37.42	120.77					26 (estimate)	61 (estimate)
CO	08	39.97	104.79	055116	Longmont	40.11	105.06	13.60	48.80
DE	10	38.87	75.44	072730	Dover	39.09	75.31	44.14	56.30
IA	19	41.65	93.47	130241	Ankeny 3 S	41.41	93.36	32.18	48.10
KS	20	38.97	97.09	141559	Clay Center	39.23	97.07	30.48	55.20
MI	26	41.75	83.70	200032	Adrian 2 NNE	41.55	84.01	34.15	47.90
NV	32	40.72	117.04	263245	Golconda	40.57	117.29	7.58	50.00
NC	37	35.87	80.27	319675	Yadkinville 6 E	36.08	80.31	45.07	58.00
ND	38	46.88	97.17	321686	Colgate	47.14	97.39	17.76	40.40
OH	39	40.38	83.06	334942	Marion 2 N	40.37	83.08	36.91	49.20
WA	53	47.06	118.42	454679	Lind 3 NE	47.00	118.35	9.37	49.70
WI	55	44.49	89.23	022462	Rosholt 9 NNE	44.46	89.15	32.91	42.90

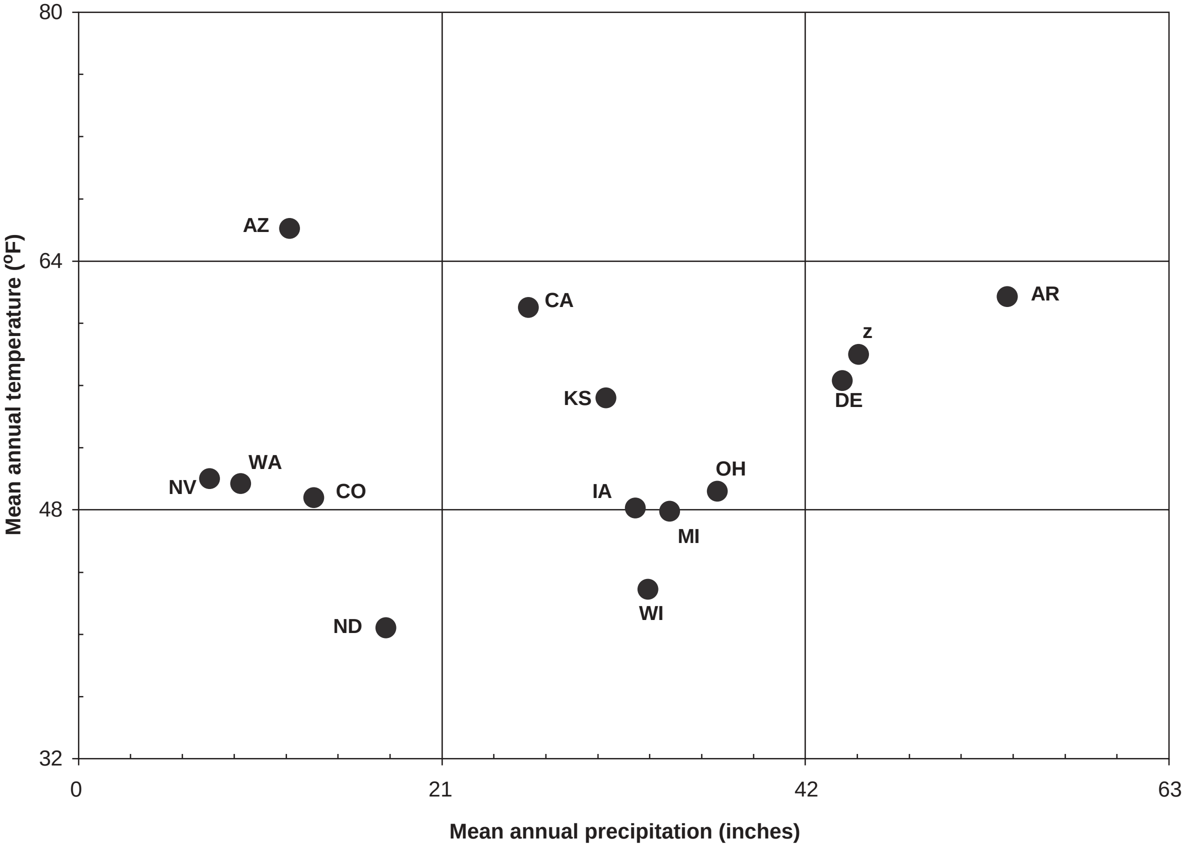

Figure 6. Distribution of SPS-2 sites with respect to precipitation and temperature.

TABLE 28 Presence of filter fabric below permeable-asphalt treated base in SPS-2 sections designed to be drained

	Sections with drained permeable asphalt-treated base			
	Section number			
State	0209	0210	0211	0212
CA 06	no	no	no	no
DE 10	no	no	no	no
KS 20	no	no	no	no
NV 32	no	no	no	no
NC 37	no	no	no	no
OH 39	no	no	no	no
WA 53	no	no	no	no
	Section number			
	0221	0222	0223	0224
AZ 04	no	no	no	no
AR 05	yes*	yes*	yes*	yes*
CO 08	no	no	no	no
IA 19	yes	yes	yes	yes
MI 26	no	no	no	no
ND 38	no	no	no	no
WI 55	no	no	no	no

* The regional support center reports that geotextile was placed below the PATB, although this is not reflected in LTPP database release 12.0.

TABLE 29 Age and accumulated flexible pavement equivalent standard axle loads (ESALs) of SPS-2 sites at time of analysis

State	Age, years	Accumulated rigid pavement ESALs, millions	Accumulated ESALS Divided by age
Arizona	7.18	8.78	1.22
Arkansas	5.04	10.89	2.16
California	Data unavailable	Data unavailable	Data unavailable
Colorado	6.78	2.14	0.32
Delaware	4.60	2.00	0.43
Iowa	5.47	0.38	0.07
Kansas	8.78	6.52	0.74
Michigan	6.46	11.48	1.78
Nevada	5.64	4.45	0.79
North Carolina	6.90	8.98	1.30
North Dakota	5.73	Data unavailable	Data unavailable
Ohio	4.51	2.83	0.63
Wahington	4.66	1.61	0.35
Wisconsin	2.60	Data unavailable	Data unavailable
Average	**6.00**	**5.46**	**0.89**

in Appendix A). The completed data forms for each site were furnished to the NCHRP Project 1-34C research team for use in this study. Highlights of the inspections are summarized in Appendix B. The test section layout diagrams in Appendix B show the locations of the edgedrain outlets inspected.

Observations on Results of Field Inspections

A summary of the drains inspected and not inspected is given in Table 31. In cases where an outlet was located outside the limits of any test section, it was assumed to be associated with the nearest test section. Just as with the SPS-1 inspections, instances of the following discrepancies were found in the SPS-2 inspections:

- Some instances of test sections that should not be drained (test sections numbered 0201 through 0208 or 0213 through 0220, depending on the site), but at which lateral outlets were found and marked for inspection. These are indicated by a "*y*" in some cells in the first eight test section columns in Table 31. Note that for the Arkansas,

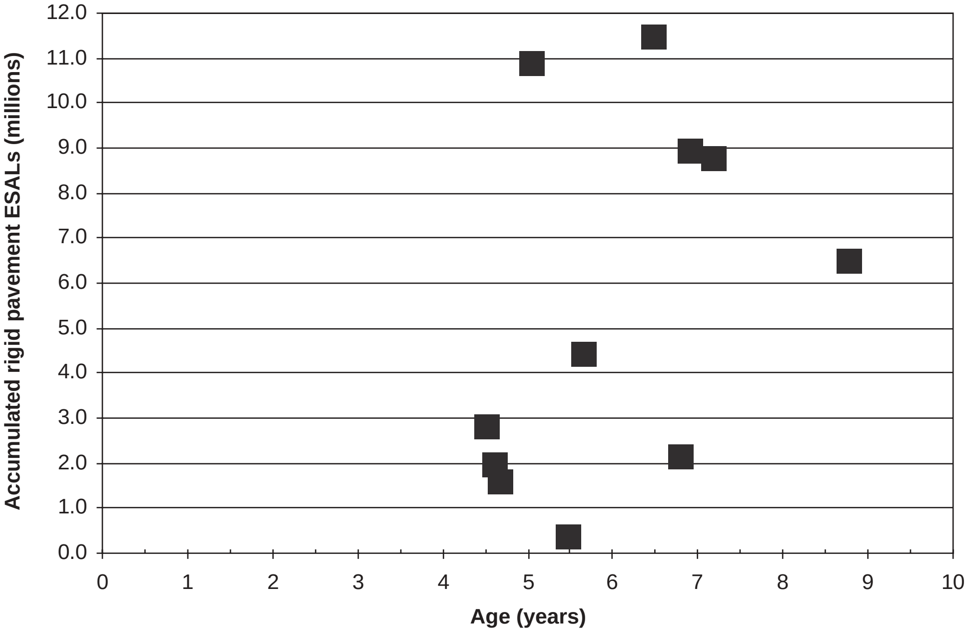

Figure 7. Age versus accumulated rigid ESALs for SPS-2 sites with traffic data available.

TABLE 30 SPS-2 construction problems and deviations at sites with information available

SHRP ID	State	Problem or Deviation
040200	AZ	Cracking developed immediately in the PCC[1] surfacing in those sections placed over the LCB[2]. This only occurred in the passing lane. The 900-psi concrete strengths were actually in the low 800's. The 550-psi and 900-psi one-year strengths are relatively close together.
050200	AR	No major deviations, although at station 2+50 on section 8, the paver's augers became entangled with the dowel assembly. The contractor removed the entire affected area (dowel assembly and concrete) and repaired the area. Also did not seal longitudinal joints. Pumping became evident and joints were sealed in 1997.
080200	CO	Site is half new alignment and half reconstruction. Some sections cut, some fill. Material testing showed subgrade to be fine grained for some sections and coarse for others. One low-volume interchange near beginning of test sections. Subgrade was very wet during construction. Significant pumping [?] was evident prior to LCB placement on most sections. Much of PATB[3] was contaminated with fines in the mixture. Appeared to drain, however. Different coarse aggregates were used for the 550 and 900 psi concretes. One-year PCC strength values do not exhibit the differences as placed. Final strengths are much closer together.
100200	DE	Eight of the twelve sections contained partial shallow cuts but the cut subgrades had to meet type 'A' borrow specifications. Those cut subgrades that did not mee the type 'A' specifications were excavated to receive 12 inches of type 'A' borrow (with prior approval). A transverse construction joint was placed in section 102012. In sections 100203, 100207, and 100211, the longitudinal joint was sawn 5 days after the concrete placement. Bases did not extend the full width of the shoulder (with prior approval). Neoprene was used in the transverse joints (hot pour in three sections where the joints were rough) and hot-poured rubberized asphalt in the longitudinal joint. No joint sealant was used between the mainline concrete pavement and the asphalt shoulder. Joint sealing was done in 1996 and in the second construction season. The road was opened to construction traffic before joint sealing. In sections 100209, 100210, 100211, and 100212, edge drains were not located at the outside edges of the shoulder. Edge drain outlets were spaced at distances greater than 250 feet. In sections 100201, 100205, and 100209, "checks" [cracks?] within test sections were repaired by removing and replacing the concrete – all repairs full width. [Six repairs listed in 100201, seventeen repairs listed in 100205, and three repairs listed in 100209. 550 flexural strength concrete not used on sections 100202, 100203, and 100211 – 3000 psi compressive strength concrete used instead. 550 flexural strength concrete used on sections 100201, 100205, and 100209 – concrete removed and replaced with 650 flexural strength concrete. Sections 100202 and 100206 were placed with 900 psi flexural strength 6½ bag mix. Concrete was later removed and replace with 900 psi flexural strength 7½ bag mix. In section 100205, profile index is greater than 10 inches per mile (24.9). Note this section is scheduled for diamond grinding.

(*continues on next page*)

TABLE 30 (*Continued*)

SHRP ID	State	Problem or Deviation
320200	NV	The natural subgrade was lime treated 1 foot deep and then convered with the embankment layer. The LCB in section 320205 showed extensive shrinkage cracking throughout just prior to PCC paving. The LCB in sections 320207 and 320208 showed random block cracking every 15 to 20 ft within 16 ft of the inner edge. The 550 psi and 900 psi design strengths were changed to 375 psi and 750 psi due to materials constraints. During paving of section 320203, the concrete in front of the paver was watered frequently by hand and by truck. From section 320211 to the end of paving, the ¾" aggregate was lowered 2% and the fine aggregate raised 2% from prior PCC paving. In section 320205, the transverse tie bars were pounded in by hand for the first 300 ft of the section. 200 feet into section 320205, the water reducer was increased to a maximum 4 percent. 300 feet into seciton 320205, the water/cement reatio was increased from 0.49 to 0.53. During paving of the second half of section 320206, the PCC in front of the DBI was watered down constantly. During paving of sections 320208, 320210, and 320211, the PCC in front of the DBI was sprayed periodically with water. Tie bars in the last 300 ft of section 320209 were pounded in by hand. Prior to paving section 320209, the PATB sagged slightly where the outlet trenches were placed, and was especially bad at station 1622+92. The PCC and PATB in section 320212 was torn out and replaced with 5" of CTB and 10.5" of NDOT PCC. Tie bars were inserted at both the centerline and lane/shoulder joints. Sections 320101, 320202, 320203, 320204, 320205, 320206, 320208, and 320210 had at least 10 meters of combined transverse and longitudinal cracking 8 months following paving, with sections 320202, 320203, 320205, and 320206 having greater than 100 meters of combined cracking. Two-way traffic during first three months.

North Carolina, and North Dakota sites, no mention of these installations is made in the construction deviation reports. Construction deviation reports are not available for the California, Ohio, and Michigan sites, among others.

- A few instances of test sections that should be drained (test sections numbered 0209 through 0212 or 0221 through 0224, depending on the site), but at which no lateral outlets within or near the sections were found or marked for inspection. These instances are indicated by an “n” rather than a “y” in some cells in the last four test section columns in Table 31.

These discrepancies were reported to LTPP in an LTPP Data Analysis/Operations Feedback Report (KTH-3, 11 June 2002) submitted by the NCHRP 1-34C research team. The responses were received from the LTPP regional support centers are summarized below.

SPS-2 test sections designed to be undrained, but drains were found and inspected:

- Arkansas 0216 and 0218—The extra outlets in Arkansas SPS-2 could have been put in to ensure that the adjacent or nearby laterals are functional. These extra laterals are full of silt and gravel and inspection was unable to pass beyond 2 to 5 ft. They can also be old lateral not removed during construction.
- California 0204—This section has a nearby ramp, which necessitated the placement of the edge drain outlets (the section itself does not have a drainage layer).

TABLE 30 (*Continued*)

SHRP ID	State	Problem or Deviation
370200	NC	Sections 370201, 370208, 370209, and 370212 contained both cut and fill. Sections 370203, 370205, 370208, 370211, and 370212 were located on curves instead of the preferred tangents. The add-on lane for monitoring and evaluating the performance of the six 8-inch PCC test sections has a different pavement structure than the adjacent mainline pavement. This add-on lane received prior approval. Section 370204 was separated from the others (with prior approval) by the Highway 64 interchange. In sections 370211 and 370212, prime that had been placed on the dense-graded aggregate base was opened to construction traffic for several weeks prior to placing the permeable asphalt-treated base. It was not an effective drainage layer. In sections 370209 and 270210, no prime was placed on the dense-graded “asphalt” [aggregate?] base prior to placing the permeable asphalt-treated base layer. In sections 370209 and 370210, 5 inches of permeable asphalt-treated base were placed instead of the specified 4 inches, for construction reasons. In section 370204, a construction joint was placed at station 137+75 due to darkness. In section 370205, contraction cracks at station 307+30 and 308+24 were repaired by removing and replacing the concrete slab. In the 8-inch PCC sections, dowels were 1 inch diameter instead of 1.25 inches. The base layers beneath all test sections were not constructed to the full width of the inside and outside shoulders. In sections 370201, 370202, 370203, 370204, 370209, 370310, 370211, and 370212, the base extends for 2 ft beyond the edge of the pavement. In sections 370207 and 370208, the base was placed to the same width as the PCC. In section 370206, 370205, the base extends 2 ft beyond the outside edge of the pavement. Filter fabric was exposed for up to 4 months. Any noted deteriorated fabric was covered with filter fabric patches. The fly ash used to counteract high alkali content exceeded 15% by weight of cement. Water spray was used to soften the concrete when it piled up ahead of the finisher.

(*continues on next page*)

- Michigan 0213 and 0220—Design plans show no outlets planned for these sections. No as-built records are available to confirm whether or not these outlets are present.
- North Carolina 0205—No edgedrains were installed. The actual station of the outlets should be checked. Is the outlet inspected an actual edgedrain outlet or boxed culvert outlet? [Note: according to the video inspection report, the inspected outlet is a 102-mm (4-inch) diameter PVC pipe.]
- Ohio 0201, 0202, 0203, 0204, 0205, 0206, 0207, and 0208—Design plans show no outlets planned for these sections. No as-built records are available to confirm whether or not these outlets are present. [Note: the video inspection reports indicate that these outlets are present but apparently capped internally.]

SPS-2 test sections designed to be drained, but drains were not found:

- Iowa 0223 and 0224—Design plans show three outlets planned for section 190223 and four outlets planned for section190224. No as-built records are available to confirm whether or not these outlets are present.
- Michigan 0222—Design plans show one outlet planned for section 260222. Design plans include a note that the outlet spacing is less than 250 ft. No as-built records are available to confirm whether or not this outlet is present.
- Nevada 0212—This section failed during construction and was released from the program (from an analysis—and the LTPP—perspective, the section never existed).
- Wisconsin 0221, 0222, 0223, 0224—Design plans show four outlets planned for section 550221, three for 550222, and two each for 550223 and 550224. No as-built records are available to confirm whether or not this outlet is present. [Note: the video inspection contractor reported that LTPP regional center support personnel visited the Wisconsin SPS2 site and could not locate any lateral outlets

TABLE 30 (*Continued*)

SHRP ID	State	Problem or Deviation
530200	WA	Section 530203 located on cut section. Remaining sections subexcavated and filled. All sections except 530202 and 530203 had a rock fill placed prior to placing fill material. Sections 530201, 530206, and 530210 had rock fill only in parts of the section. The cylinders and cores from section 530207 yielded 14- and 28-day compressive strengths up to 2.5 times higher than the other LCB sections. The 14-day LCB cylinder compressive strengths for sections 530205 and 530206 were close to 300 psi; design called for 500 to 750 psi at 7 days. (Cores at 14 days for both these sections were within specifications.) Sections 530209 and 530212 had some patching done on the fabric in the edge drains and some soil contamination occurred. Soil was accidentally placed on the PATB inner shoulder in sections 530209 and 530212, then air blown off. Some contamination of the PATB occurred. The first 300 ft of PCC in section 530207 had 47 oz/yd^3 of water reducer while the last 200 ft had 28 oz/yd^3. Surface voids were visible in the last 200 ft. Section 530203 had a PCC water/cement ratio of 0.433 in the first 250 ft and 0.450 in the last 250 ft. The inner edge slumped significantly in a few locations. The slump at station 2+50 was 2.8 inches. Section 530206 had shrinkage cracks throughout the section following pages with crack widths between ½ and 1 mm. Static modulus of elasticity cores from each section had to be redrilled and retested. Cores were tested 10 weeks after scheduled 28-day testing.

[1] Portland cement concrete
[2] Lean concrete base.
[3] Permeable asphalt-treated base.

to mark on either occasion. However, Wisconsin DOT personnel, and a research team member who visited the site, confirm that the outlets are present.]

Test sections designed to be drained but for which drainage outlets could not be located were not used in this analysis of the effects of drainage on pavement performance. Similarly, test sections designed to be undrained but at which lateral outlets were found and inspected also were not used in the analysis presented in this report.

After reviewing the forms summarizing the video inspections of the drainage installations, the 1-34C research team made a subjective assessment of whether the quality of drainage functioning in each test section was “good” or “poor.” The ratings assigned are summarized in Table 32. Conditions that garnered a “poor” rating included lateral outlets being buried or fully blocked with silt, gravel, or other debris; longitudinal drains being fully blocked; or a considerable amount of water standing in longitudinal drains and not flowing out.

Longitudinal drains and lateral outlets in a pavement structure that has been in service some years are never pristine; there is nearly always some silt accumulation and some rodents and their nests. Whether or not there is enough material present to block the flow of water in the event of a storm—or whether the flow of water caused by a storm would clear out some or all of this material—remains a matter of judgment until someone investigates this by conducting video inspections before and after storms. In general, if the amount of material described as being present did not seem sufficient to block the flow of water, a “good” rating was assigned.

In Table 32, a question mark alone in a cell indicates that no rating can be assigned because no laterals were inspected within the test section. A question mark with an asterisk indicates that a lateral was found and inspected visually, but the video camera could not be inserted in the lateral to inspect the interior of the longitudinal drain. In some cases this was because the inner diameter of the lateral was too small. In other cases this was because rodent screens were placed too far up in the lateral, out of arm’s reach, and could not be removed so that the camera could pass. In the case of the Ohio SPS-2 sections 0201 through 0208, it appears to be due to the laterals being capped internally.

EFFECTS OF DRAINAGE ON SPS-2 CONCRETE PAVEMENT PERFORMANCE

Tables 24 and 25 show that the following specific test section comparisons may be conducted to assess the effects

TABLE 31 SPS-2 test-section sections with drainage outlets inspected with video

	Test Section ID											
	0201 and 0213	0202 and 0214	0203 and 0215	0204 and 0216	0205 and 0217	0206 and 0218	0207 and 0219	0208 and 0220	0209 and 0221	0210 and 0222	0211 and 0223	0212 and 0224
	Base Type											
	Dense-graded aggregate				Lean concrete base				Permeable asphalt-treated base over aggregate			
State	Undrained								Drained			
AZ									y[1]	y	y	y
AR				y[2]		y			y	y	y	y
CA				y					y	y	y	y
CO									y	y	y	y
DE									y	y	y	y
IA									y	y	n[3]	n
KS									y	y	y	y
MI	y							y	y	n	y	y
NV									y	y	y	n
NC					y				y	y	y	y
ND									y	y	y	y
OH	y	y	y	y	y	y	y	y	y	y	y	y
WA									y	y	y	y
WI									n	n	n	n

[1] y = in unshaded cells, subdrains found and inspected

[2] y = in shaded cells, drains found and inspected, even though according to the experiment design the section should not have drains.

[3] n = subdrains not found or found but not inspected.

of drainage on pavement performance in the SPS-2 experiment, holding concrete slab thickness, strength, and width constant:

(A) *Undrained dense-graded aggregate (AGG) versus permeable asphalt-treated base (PATB):*

- 0201 versus 0209: 8-inch slab, 12 feet wide, 550 psi concrete
- 0202 versus 0210: 8-inch slab, 14 feet wide, 900 psi concrete
- 0203 versus 0211: 11-inch slab, 14 feet wide, 550 psi concrete
- 0204 versus 0212: 11-inch slab, 12 feet wide, 900 psi concrete
- 0213 versus 0221: 8-inch slab, 14 feet wide, 550 psi concrete
- 0214 versus 0222: 8-inch slab, 12 feet wide, 900 psi concrete
- 0215 versus 0223: 11-inch slab, 12 feet wide, 550 psi concrete
- 0216 versus 0224: 11-inch slab, 14 feet wide, 900 psi concrete

(B) *Undrained lean concrete base (LCB) versus permeable asphalt-treated base (PATB):*

- 0205 versus 0209: 8-inch slab, 12 feet wide, 550 psi concrete
- 0206 versus 0210: 8-inch slab, 14 feet wide, 900 psi concrete
- 0207 versus 0211: 11-inch slab, 14 feet wide, 550 psi concrete
- 0208 versus 0212: 11-inch slab, 12 feet wide, 900 psi concrete
- 0217 versus 0221: 8-inch slab, 14 feet wide, 550 psi concrete
- 0218 versus 0222: 8-inch slab, 12 feet wide, 900 psi concrete
- 0219 versus 0223: 11-inch slab, 12 feet wide, 550 psi concrete
- 0220 versus 0224: 11-inch slab, 14 feet wide, 900 psi concrete

The sites with test sections useful to each of the above comparisons were identified by combining the information about which test sections had drainage inspected (Table 31)

TABLE 32 Subjective ratings of drainage functioning at SPS-1 test sections based on video inspection results

	Test Section ID											
	0201 and 0213	0202 and 0214	0203 and 0215	0204 and 0216	0205 and 0217	0206 and 0218	0207 and 0219	0208 and 0220	0209 and 0221	0210 and 0222	0211 and 0223	0212 and 0224
	Base Type											
	Dense-graded aggregate				Lean concrete base				Permeable asphalt-treated base over aggregate			
State	Undrained								Drained			
AZ									G[1]	G	G	G
AR				P[2]		P			P	P	P	P
CA				P					G	G	G	P
CO									G	P	P	P
DE									P	G	P	G
IA									P	P	?	?
KS									G	G	G	G
MI	P							P	P	?	P	P
NV									G	G	G	?
NC					P				P	P	P	P
ND									G	G	G	G
OH	?*[3]	?*	?*	?*	?*	?*	?*	?*	G	P	G	P
WA									G	G	G	G
WI									?	?	?	?

[1] G = Drainage function rated as good.
[2] P = Drainage function rated as poor.
[3] ?* = Camera could not be inserted.

with the information about the subjective ratings of drainage functioning (Table 32).

For each of the two sets of comparisons listed, and for each pavement performance indicator considered (IRI, transverse cracking, and longitudinal cracking), paired *t*-tests were conducted to determine whether or not the mean difference between the undrained and drained test section pairs was significant. (Due to irregularities in the available faulting data, as discussed more later, statistical analyses of faulting were not conducted.) Three paired *t*-tests were conducted each time:

- For the subset of test section pairs with drainage functioning rated as good (denoted by G in the column "Drainage functioning" in Tables 33 through 38),
- For the subset of test section pairs rated as poor (denoted by P in the column "Drainage functioning" in Tables 33 through 38), and
- For all valid test section pairs regardless of drainage functioning (denoted by G, P, or ? in Tables 33 through 38).

The test section pairs excluded from these comparisons were:

- Those that had subdrainage outlets located and inspected in the section that was designed to be undrained (denoted by X in Tables 33 through 38), and
- Those lacking measurement data for one or both of the test sections (denoted by --- in Tables 33 through 38).

The difference in the performance measures (IRI, transverse cracking, or longitudinal cracking) for each test section pair is calculated as the measured value for the undrained section minus the measured value for the drained section. Thus, a positive difference indicates that the measured value was greater in the undrained section, and a negative difference indicates that the measured value was greater in the drained section.

The mean difference for all the pairs considered is the sum of the pairwise differences divided by the number of pairs. Whether or not the mean difference is significant (at a selected significance level, e.g., 95 percent) is determined by calculating the lower and upper limits of (95-percent) confidence interval around the mean difference. If zero is not contained within the lower and upper limits of the confidence interval, the mean difference can be concluded, with 95 percent confidence, to be significantly different than zero.

Effect of Drainage on Concrete Pavement Roughness (IRI) Development

For each SPS-2 site, IRI data were extracted from the MON_PROFILE_MASTER table in the LTPP database. An IRI for each run was calculated as the average of the run's left and right wheelpath IRIs. An average IRI for each testing date was then calculated as the average of the run IRIs for that date—most often five runs, but sometimes as few as one or as many as fifteen.

The expectation is that IRI will tend to increase over time, as the pavement deteriorates. However, IRI does not always increase steadily over time. Sometimes the IRI of a test section is lower than the IRI measured on the same test section a year earlier, a month earlier, or even a day earlier. Physical reasons why IRI might decrease from one testing date to the next include the following (from Reference 4):

- Rehabilitation or maintenance between testing dates;
- Seasonal variation;
- Measurement in different paths;
- Different starting locations;
- Spikes in the data caused by reflection of light from the white paint stripe at the start of a test section; or
- Problems with the profilometer electronics, sensors, or distance measurement.

However, it is not necessarily true that an IRI decrease, or an IRI increase for that matter, always has a physical explanation. Some portion of the variation seen in IRI data is random variation. That is, some fluctuations in IRI, both upward and downward, are not significantly different than no change at all.

The first available IRI is not necessarily the IRI immediately after opening to traffic. The first testing date for which IRI data are available for all or most of the test sections at a site may be a year or more after the opening date. (Note that the date of opening to traffic is shown for each site in the ESAL calculation summary in Appendix B.) Similarly, the latest IRI measurements used in the analysis are not necessarily those for the latest IRI measurement date at any one test section at a site, but rather those for the latest IRI measurement date for which measurements are available for most or all of the sections at a site. The IRI histories of the test sections at each SPS-2 site are shown in Appendix B.

The comparisons of IRI change between drained and undrained sections of matching designs are shown in Tables 33 and 34. Which comparisons were deemed possible was assessed on the basis of the drainage detection and drainage functioning information summarized in Tables 31 and 32.

Table 33 shows the comparisons of undrained aggregate base (AGG) versus permeable asphalt-treated base (PATB). The change in IRI was slightly greater (as indicated by a positive mean difference in change in IRI) in the undrained AGG sections than in the drained PATB sections of otherwise like design. This difference was found to be statistically significant when all drained sections were considered together, but not when sections with drainage functioning subjectively rated as good were separated from those with drainage functioning rated as poor. The mean difference in IRI change was slightly greater for sections with poor drainage functioning than for sections with good drainage functioning. This—to the extent that the subjective ratings of drainage functioning are accurate—suggests that quality of drainage is not a significant factor in the differences observed.

Table 34 shows the comparisons of undrained lean concrete base (LCB) versus permeable asphalt-treated base (PATB). The change in IRI was slightly greater in the undrained LCB sections than in the drained PATB sections, but the differences were not found to be significant in any of the cases considered (good drainage functioning, poor drainage functioning, or the two combined). Again, the mean difference in IRI change between undrained and drained sections was greater for PATB sections with poor drainage functioning than PATB sections with good drainage functioning, which tends to discount quality of drainage as a significant factor.

Effect of Drainage on Concrete Pavement Faulting Development

The faulting histories of the SPS-2 sites are shown in Appendix B. The estimated accumulated ESALs corresponding to the most recent faulting measurements are reported in Appendix B. The accumulated ESAL values are slightly different than those reported earlier for the IRI histories, since faulting and IRI were measured on different dates.

The faulting histories for the SPS-2 sites do not demonstrate the more or less consistently increasing trend with time that is normally expected. The average faulting for the different test sections increases and decreases erratically from measurement date to measurement date; and, in some cases, the average faulting changes from positive to negative to positive again. This may be due to the very small magnitudes of faulting measured: a lot of small-negative measurements, zero measurements, and small-positive measurements may result in erratic average values. When larger magnitudes of faulting develop—such that the averages are consistently being calculated from positive measurements—trends in faulting with time and traffic may become more evident.

Effect of Drainage on Concrete Pavement Cracking Development

Data for three types of cracking in SPS-2 pavements were extracted from the LTPP database:

- Corner breaks;
- Transverse cracking (all severities, sealed and unsealed); and
- Longitudinal cracking (all severities, sealed and unsealed).

TABLE 33 Change in International Roughness Index (IRI) in SPS-1 undrained dense-graded aggregate (AGG) base sections versus drained permeable asphalt-treated base (PATB) sections

	IRI		Age, years	Drainage function-ing	Difference in IRI		
	AGG	PATB			All	Good	Poor
Site	**0201**	**0209**					
CA 06	---[1]	---	---	---			
DE 10	0.355	0.061	3.19	P[2]	0.294		0.294
KS 20	0.538	0.006	8.17	G[3]	0.532	0.532	
NV 32	1.172	0.192	3.97	G	0.980	0.980	
NC 37	0.214	0.046	4.04	P	0.168		0.168
OH 39	0.205	0.093	4.01	X[4]			
WA 53	0.142	0.106	4.61	G	0.036	0.036	
Site	**0202**	**0210**					
CA 06	---	---	---	---			
DE 10	0.122	0.072	3.19	G	0.050	0.050	
KS 20	-0.013	0.060	8.17	G	-0.073	-0.073	
NV 32	0.621	0.096	0.82	G	0.525	0.525	
NC 37	0.050	0.110	4.04	P	-0.060		-0.060
OH 39	0.248	0.089	4.01	X			
WA 53	0.027	0.239	4.61	G	-0.212	-0.212	
Site	**0203**	**0211**					
CA 06	---	---	---	---			
DE 10	-0.042	0.033	3.19	P	-0.075		-0.075
KS 20	0.007	0.094	8.17	G	-0.087	-0.087	
NV 32	0.205	0.311	3.97	G	-0.106	-0.106	
NC 37	0.116	-0.024	4.04	P	0.140		0.140
OH 39	-0.067	-0.034	4.01	X			
WA 53	0.061	-0.023	4.61	G	0.084	0.084	
Site	**0204**	**0212**					
CA 06	---	---	---	---			
DE 10	0.073	0.050	3.19	G	0.023	0.023	
KS 20	-0.167	-0.023	8.17	G	-0.144	-0.144	
NV 32	0.420	0.288	3.97	?[5]	0.132		
NC 37	0.121	0.002	4.04	P	0.119		0.119
OH 39	-0.008	-0.079	4.01	X			
WA 53	0.031	0.127	4.61	G	-0.096	-0.096	
Site	**0213**	**0221**					
AZ 04	0.301	0.064	6.86	G	0.237	0.237	
AR 05	0.362	0.075	3.78	P	0.287		0.287
CO 08	-0.010	-0.065	6.33	G	0.055	0.055	
IA 19	-0.110	0.170	5.26	P	-0.280		-0.280
MI 26	1.151	0.074	4.60	X			
ND 38	-0.025	-0.065	2.07	G	0.040	0.040	
WI 55	0.469	0.239	2.40	?	0.230		
Site	**0214**	**0222**					
AZ 04	-0.122	-0.076	6.86	G	-0.046	-0.046	
AR 05	0.585	-0.064	3.78	P	0.649		0.649
CO 08	-0.088	0.012	6.33	P	-0.100		-0.100
IA 19	0.080	-0.040	5.26	P	0.120		0.120
MI 26	0.216	-0.068	4.60	?	0.284		
ND 38	-0.067	-0.070	2.07	G	0.003	0.003	
WI 55	0.316	0.150	1.58	?	0.166		
Site	**0215**	**0223**					
AZ 04	0.341	0.165	6.86	G	0.176	0.176	
AR 05	0.224	0.106	3.78	P	0.118		0.118
CO 08	0.075	-0.123	6.33	P	0.198		0.198
IA 19	0.034	-0.155	5.26	?	0.189		
MI 26	0.733	-0.017	4.60	P	0.750		0.750
ND 38	0.051	-0.067	2.07	G	0.118	0.118	
WI 55	0.144	0.187	2.40	?	-0.043		
Site	**0216**	**0224**					
AZ 04	-0.052	0.088	6.86	G	-0.140	-0.140	
AR 05	0.549	0.042	3.78	X			
CO 08	-0.001	-0.036	6.33	P	0.035		0.035
IA 19	-0.013	-0.063	5.26	?	0.050		
MI 26	-0.120	-0.079	4.60	P	-0.041		-0.041
ND 38	0.031	-0.053	2.07	G	0.084	0.084	
WI 55	0.139	0.204	2.40	?	-0.065		
Mean difference					0.115	0.093	0.145
N					46	22	16
S_D					0.248	0.274	0.264
$t_{alpha/2,\ n-1}$					2.481	2.595	2.687
Confidence interval lower limit					0.025	-0.059	-0.032
Confidence interval upper limit					0.206	0.244	0.322
Significant difference (Overall confidence level = 95%)					yes	no	no

[1] --- = lacking measurement data for one or both test sections.
[2] P = Drainage function rated as poor.
[3] G = Drainage function rated as good.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] ? = Drainage outlets not found.

TABLE 34 Change in International Roughness Index (IRI) in SPS-2 undrained lean concrete base (LCB) sections versus drained permeable asphalt treated base (PATB) sections

	IRI		Age, years	Drainage functioning	Difference in IRI		
	LCB	**PATB**			**All**	**Good**	**Poor**
Site	**0205**	**0209**					
CA 06	---[1]	---	---	---			
DE 10	0.144	0.061	3.19	P[2]	0.083		0.083
KS 20	0.177	0.006	8.17	G[3]	0.171	0.171	
NV 32	0.298	0.192	3.97	G	0.106	0.106	
NC 37	0.156	0.046	4.04	X[4]			
OH 39	0.123	0.093	4.01	X			
WA 53	0.019	0.106	4.61	G	-0.087	-0.087	
Site	**0206**	**0210**					
CA 06	---	---	---	---			
DE 10	0.124	0.072	3.19	G	0.052	0.052	
KS 20	0.070	0.060	8.17	G	0.010	0.010	
NV 32	0.122	0.096	0.82	G	0.026	0.026	
NC 37	0.038	0.110	4.04	P	-0.072		-0.072
OH 39	0.180	0.089	4.01	X			
WA 53	1.005	0.239	4.61	G	0.766	0.766	
Site	**0207**	**0211**					
CA 06	---	---	---	---			
DE 10	0.029	0.033	3.19	P	-0.004		-0.004
KS 20	0.097	0.094	8.17	G	0.003	0.003	
NV 32	0.222	0.311	3.97	G	-0.089	-0.089	
NC 37	0.036	-0.024	4.04	P	0.060		0.060
OH 39	0.060	-0.034	4.01	X			
WA 53	0.134	-0.023	4.61	G	0.157	0.157	
Site	**0208**	**0212**					
CA 06	---	---	---	---			
DE 10	0.013	0.050	3.19	G	-0.037	-0.037	
KS 20	0.084	-0.023	8.17	G	0.107	0.107	
NV 32	0.013	0.288	3.97	?[5]	-0.275		
NC 37	-0.032	0.002	4.04	P	-0.034		-0.034
OH 39	-0.045	-0.079	4.01	X			
WA 53	0.364	0.127	4.61	G	0.237	0.237	
Site	**0217**	**0221**					
AZ 04	-0.110	0.064	6.86	G	-0.174	-0.174	
AR 05	0.133	0.075	3.78	P	0.058		0.058
CO 08	0.098	-0.065	6.33	G	0.163	0.163	
IA 19	0.363	0.170	5.26	P	0.193		0.193
MI 26	2.149	0.074	4.60	P	2.075		2.075
ND 38	0.105	-0.065	2.07	G	0.170	0.170	
WI 55	0.043	0.239	2.40	?	-0.196		
Site	**0218**	**0222**					
AZ 04	-0.355	-0.076	6.86	G	-0.279	-0.279	
AR 05	0.042	-0.064	3.78	X			
CO 08	-0.073	0.012	6.33	P	-0.085		-0.085
IA 19	0.054	-0.040	5.26	P	0.094		0.094
MI 26	0.358	-0.068	4.60	?	0.426		
ND 38	-0.026	-0.070	2.07	G	0.044	0.044	
WI 55	-0.103	0.134	2.40	?	-0.237		

(*continues on next page*)

TABLE 34 ***(Continued)***

Site	0219	0223					
AZ 04	0.096	0.165	6.86	G	-0.069	-0.069	
AR 05	0.121	0.106	3.78	P	0.015		0.015
CO 08	0.070	-0.123	6.33	P	0.193		0.193
IA 19	-0.068	-0.155	5.26	?	0.087		
MI 26	0.178	-0.017	4.60	P	0.195		0.195
ND 38	0.053	-0.067	2.07	G	0.120	0.120	
WI 55	0.236	0.187	2.40	?	0.049		
Site	**0220**	**0224**					
AZ 04	-0.094	0.088	6.86	G	-0.182	-0.182	
AR 05	0.319	0.042	3.78	P	0.277		0.277
CO 08	0.132	-0.036	6.33	P	0.168		0.168
IA 19	0.030	-0.063	5.26	?	0.093		
MI 26	0.024	-0.079	4.60	X			
ND 38	0.123	-0.053	2.07	G	0.176	0.176	
WI 55	0.065	0.204	2.40	?	-0.139		
Mean difference					0.098	0.063	0.214
N					45	22	15
S_D					0.354	0.207	0.526
$t_{alpha/2, n-1}$					2.483	2.595	2.711
Confidence interval lower limit					-0.033	-0.051	-0.154
Confidence interval upper limit					0.229	0.178	0.582
Significant difference (Overall confidence level = 95%)					no	no	no

[1] --- = lacking measurement data for one or both test sections.
[2] P = Drainage function rated as poor.
[3] G = Drainage function rated as good.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] ? = Drainage outlets not found.

There were very few SPS-2 pavement sections with corner breaks, and there were almost never more than one or two corner breaks in the test section. Thus, the number of corner breaks in each section where they occurred was multiplied by 2 meters, and added to the total length of transverse cracking in meters. Separately, the total length of longitudinal cracking was determined for each pavement section.

Because of the large proportion of test sections that still have no transverse and/or longitudinal cracking, the cracking histories of the SPS-2 sites are not shown in Appendix B. However, a statistical examination of the most recently noted levels of transverse and longitudinal cracking is possible.

The comparisons of transverse cracking between drained and undrained sections of matching designs are shown in Tables 35 and 36. Which comparisons were deemed possible was assessed on the basis of the drainage detection and drainage functioning information summarized in Tables 31 and 32. It should be noted an unusually large amount of cracking has occurred in several sections at the Nevada SPS-2 site, which had a great many problems with slab cracking during and soon after construction.

Table 35 shows the comparisons of undrained aggregate base (AGG) versus permeable asphalt-treated base (PATB). Transverse cracking was slightly greater (as indicated by a positive mean difference) in the undrained AGG sections than in the drained PATB sections of otherwise like design. The difference was not, however, found to be statistically significant for sections with good drainage functioning, poor drainage functioning, or the two groups considered together. The mean difference in transverse cracking was greater for sections with good drainage functioning than sections with poor drainage functioning, which suggests that quality of drainage may play a role in the slight differences observed.

Table 36 shows the comparisons of undrained lean concrete base (LCB) versus permeable asphalt-treated base (PATB). Transverse cracking was slightly greater in the undrained LCB sections than in the drained PATB sections, but the differences were not found to be significant in any of the cases considered (good drainage functioning, poor drainage functioning, or the two combined). Again, the mean difference in transverse cracking was greater for sections with good drainage functioning than sections with poor drainage functioning, which suggests that quality of drainage may play a role in the slight differences observed.

The comparisons of longitudinal cracking are presented in Tables 37 and 38. Which comparisons were deemed possible was assessed on the basis of the drainage detection and drainage functioning information summarized in Tables 31 and 32. It should be again noted that an unusually large amount of cracking has occurred in several sections at the Nevada

TABLE 35 Transverse cracking in meters in SPS-2 undrained dense-graded aggregate (AGG) sections versus drained permeable asphalt-treated base (PATB) sections

Base Type	AGG	PATB	Age, years	Drainage functioning	Difference		
Drained	N	Y			All	Good	Poor
Site	**0201**	**0209**					
CA 06	---[1]	---	---	---			
DE 10	0	0	4.11	P[2]	0		0
KS 20	3	0	4.82	G[3]	3	3	
NV 32	85	1	5.64	G	84	84	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X[4]			
WA 53	0	0	4.52	G	0	0	
Site	**0202**	**0210**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	1	0	4.82	G	1	1	
NV 32	153	58	1.75	G	95	95	
NC 37	0	0	6.26	P	0		0
OH 39	6	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0203**	**0211**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	P	0		0
KS 20	0	0	4.82	G	0	0	
NV 32	423	11	5.64	G	412	412	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0204**	**0212**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	0	0	4.82	G	0	0	
NV 32	42	---	5.64	---			
NC 37	0	0	6.26	P	0		0
OH 39	4	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0213**	**0221**					
AZ 04	0	0	6.45	G	0	0	
AR 05	2	0	4.66	P	2		2
CO 08	0	0	6.55	G	0	0	
IA 19	0	0	5.19	P	0		0
MI 26	13	0	5.01	X			
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0214**	**0222**					
AZ 04	0	0	6.45	G	0	0	
AR 05	0	0	4.66	P	0		0
CO 08	0	0	6.55	P	0		0
IA 19	0	0	5.19	P	0		0
MI 26	0	0	5.96	?[5]	0		
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0215**	**0223**					
AZ 04	0	0	6.45	G	0	0	
AR 05	0	0	4.66	P	0		0
CO 08	0	0	6.55	P	0		0
IA 19	0	0	5.19	?	0		
MI 26	7	0	5.96	P	7		7
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0216**	**0224**					
AZ 04	0	0	6.45	G	0	0	
AR 05	0	2	4.66	X			
CO 08	0	0	6.55	P	0		0
IA 19	0	0	5.19	?	0		
MI 26	0	0	5.96	P	0		0
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Mean difference					14.7	27.0	0.6
n					41	22	16
S_D					66.5	89.9	1.8
$t_{alpha/2,\ n-1}$					2.493	2.595	2.687
Confidence interval lower limit					-11.2	-22.7	-0.6
Confidence interval upper limit					40.6	76.8	1.8
Significant difference (Overall confidence level = 95%)					no	no	no

[1] --- = lacking measurement data for one or both test sections.
[2] P = Drainage function rated as poor.
[3] G = Drainage function rated as good.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.

TABLE 36 Transverse cracking in meters in SPS-2 undrained lean concrete base (LCB) sections versus drained permeable asphalt-treated base (PATB) sections

Base Type	LCB	PATB	Age, years	Drainage functioning	Difference		
Drained	N	Y			All	Good	Poor
Site	**0205**	**0209**					
CA 06	---[1]	---	---	---			
DE 10	29	0	4.11	P[2]	29		29
KS 20	0	0	7.33	G[3]	0	0	
NV 32	234	1	5.64	G	233	233	
NC 37	6	0	6.26	X[4]			
OH 39	26	0	4.51	X			
WA 53	1	0	4.52	G	1	1	
Site	**0206**	**0210**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	0	0	7.33	G	0	0	
NV 32	253	58	1.75	G	195	195	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	2.94	X			
WA 53	10	0	4.52	G	10	10	
Site	**0207**	**0211**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	P	0		0
KS 20	0	0	7.33	G	0	0	
NV 32	36	11	5.64	G	25	25	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	2	0	4.52	G	2	2	
Site	**0208**	**0212**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	0	0	7.33	G	0	0	
NV 32	118	---	5.64	---			
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0217**	**0221**					
AZ 04	12	0	6.45	G	12	12	
AR 05	0	0	4.66	P	0		0
CO 08	0	0	6.55	G	0	0	
IA 19	13	0	5.19	P	13		13
MI 26	0	0	3.56	P	0		0
ND 38	17	0	5.71	G	17	17	
WI 55	---	---	---	---			
Site	**0218**	**0222**					
AZ 04	16	0	6.45	G	16	16	
AR 05	37	0	4.66	X			
CO 08	4	0	6.55	P	4		4
IA 19	0	0	5.19	P	0		0
MI 26	44	0	1.59	?[5]	44		
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0219**	**0223**					
AZ 04	0	0	6.45	G	0	0	
AR 05	0	0	4.66	P	0		0
CO 08	0	0	6.55	P	0		0
IA 19	0	0	5.19	?	0		
MI 26	0	0	5.96	P	0		0
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0220**	**0224**					
AZ 04	0	0	6.45	G	0	0	
AR 05	0	2	4.66	P	-2		-2
CO 08	2	0	6.55	P	2		2
IA 19	0	0	5.19	?	0		
MI 26	0	0	5.96	X			
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Mean difference					15.0	23.2	3.1
N					40	22	15
S_D					47.4	62.4	8.0
$t_{alpha/2, n-1}$					2.496	2.595	2.711
Confidence interval lower limit					-3.7	-11.3	-2.5
Confidence interval upper limit					33.7	57.8	8.7
Significant difference (Overall confidence level = 95%)					no	no	no

[1] --- = lacking measurement data for one or both test sections.
[2] P = Drainage function rated as poor.
[3] G = Drainage function rated as good.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] ? = Drainage outlets not found.

TABLE 37 Longitudinal cracking in meters in SPS-2 undrained aggregate base (AGG) sections versus drained permeable asphalt-treated base (PATB) sections

Base Type	AGG	PATB	Age, years	Drainage functioning	Difference		
Drained	**N**	**Y**			**All**	**Good**	**Poor**
Site	**0201**	**0209**					
CA 06	---[1]	---	---	---			
DE 10	0	0	4.11	P[2]	0		0
KS 20	8	0	4.82	G[53]	8	8	
NV 32	119	4	5.64	G	115	115	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X[4]			
WA 53	0	0	4.52	G	0	0	
Site	**0202**	**0210**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	0	0	4.82	G	0	0	
NV 32	339	12	1.75	G	327	327	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0203**	**0211**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	P	0		0
KS 20	0	0	4.82	G	0	0	
NV 32	206	9	5.64	G	197	197	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0204**	**0212**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	0	0	4.82	G	0	0	
NV 32	0	---	5.64	---			
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0213**	**0221**					
AZ 04	8	3	6.45	G	5	5	
AR 05	53	0	4.66	P	53		53
CO 08	0	3	6.55	G	-3	-3	
IA 19	0	0	5.19	P	0		0
MI 26	0	0	5.01	X			
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0214**	**0222**					
AZ 04	0	3	6.45	G	-3	-3	
AR 05	0	0	4.66	P	0		0
CO 08	0	1	6.55	P	-1		-1
IA 19	0	7	5.19	P	-7		-7
MI 26	0	0	5.96	?[5]	0		
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0215**	**0223**					
AZ 04	0	0	6.45	G	0	0	
AR 05	0	0	4.66	P	0		0
CO 08	0	0	6.55	P	0		0
IA 19	0	0	5.19	?	0		
MI 26	0	0	5.96	P	0		0
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0216**	**0224**					
AZ 04	0	1	6.45	G	-1	-1	
AR 05	0	0	4.66	X			
CO 08	0	0	6.55	P	0		0
IA 19	0	5	5.19	?	-5		
MI 26	0	0	5.96	P	0		0
ND 38	0	8	5.71	G	-8	-8	
WI 55	---	---	---	---			
Mean difference					16.5	29.0	2.8
n					41	22	16
S_D					61.4	81.9	13.5
$t_{alpha/2, n-1}$					2.493	2.595	2.687
Confidence interval lower limit					-7.4	-16.3	-6.3
Confidence interval upper limit					40.4	74.2	11.9
Significant difference (Overall confidence level = 95%)					no	no	no

[1] --- = lacking measurement data for one or both test sections.
[2] P = Drainage function rated as poor.
[3] G = Drainage function rated as good.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] ? = Drainage outlets not found.

TABLE 38 Longitudinal cracking in meters in SPS-2 undrained lean concrete base (LCB) sections versus drained permeable asphalt-treated base (PATB) sections

Base Type	LCB	PATB	Age, years	Drainage functioning	Difference		
Drained	N	Y			All	Good	Poor
Site	**0205**	**0209**					
CA 06	---[1]	---	---	---			
DE 10	6	0	4.11	P[2]	6		6
KS 20	0	0	7.33	G[3]	0	0	
NV 32	271	4	5.64	G	267	267	
NC 37	1	0	6.26	X[4]			
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0206**	**0210**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	2	0	7.33	G	2	2	
NV 32	273	12	1.75	G	261	261	
NC 37	0	0	6.26	P	0		0
OH 39	21	0	2.94	X			
WA 53	2	0	4.52	G	2	2	
Site	**0207**	**0211**					
CA 06	---	---	---	---			
DE 10	45	0	4.11	P	45		45
KS 20	0	0	7.33	G	0	0	
NV 32	35	9	5.64	G	26	26	
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0208**	**0212**					
CA 06	---	---	---	---			
DE 10	0	0	4.11	G	0	0	
KS 20	0	0	7.33	G	0	0	
NV 32	33	---	5.64	---			
NC 37	0	0	6.26	P	0		0
OH 39	0	0	4.51	X			
WA 53	0	0	4.52	G	0	0	
Site	**0217**	**0221**					
AZ 04	12	3	6.45	G	9	9	
AR 05	50	0	4.66	P	50		50
CO 08	13	3	6.55	G	10	10	
IA 19	0	0	5.19	P	0		0
MI 26	6	0	3.56	P	6		6
ND 38	43	0	5.71	G	43	43	
WI 55	---	---	---	---			
Site	**0218**	**0222**					
AZ 04	15	3	6.45	G	12	12	
AR 05	37	0	4.66	X			
CO 08	0	1	6.55	P	-1		-1
IA 19	0	7	5.19	P	-7		-7
MI 26	20	0	1.59	?[5]	20		
ND 38	4	0	5.71	G	4	4	
WI 55	---	---	---	---			
Site	**0219**	**0223**					
AZ 04	0	0	6.45	G	0	0	
AR 05	0	0	4.66	P	0		0
CO 08	0	0	6.55	P	0		0
IA 19	0	0	5.19	?	0		
MI 26	0	0	5.96	P	0		0
ND 38	0	0	5.71	G	0	0	
WI 55	---	---	---	---			
Site	**0220**	**0224**					
AZ 04	0	1	6.45	G	-1	-1	
AR 05	0	0	4.66	P	0		0
CO 08	0	0	6.55	P	0		0
IA 19	0	5	5.19	?	-5		
MI 26	0	0	5.96	X			
ND 38	0	8	5.71	G	-8	-8	
WI 55	---	---	---	---			
Mean difference					18.5	28.5	6.6
N					40	22	15
S_D					58.5	77.0	16.9
$t_{alpha/2, n-1}$					2.496	2.595	2.711
Confidence interval lower limit					-4.6	-14.1	-5.2
Confidence interval upper limit					41.6	71.1	18.4
Significant difference (Overall confidence level = 95%)					no	no	no

[1] --- = lacking measurement data for one or both test sections.
[2] P = Drainage function rated as poor.
[3] G = Drainage function rated as good.
[4] X = Subdrainage outlets located and inspected in the section that was designed to be undrained.
[5] ? = Drainage outlets not found.

SPS-2 site, which had a great many problems with slab cracking during and soon after construction.

Table 37 shows the comparisons of undrained aggregate base (AGG) versus drained permeable asphalt-treated base (PATB). Longitudinal cracking was slightly greater (as indicated by a positive mean difference) in the undrained AGG sections than in the drained PATB sections of otherwise like design. The difference was not, however, found to be statistically significant for sections with good drainage functioning, poor drainage functioning, or the two groups considered together. The mean difference in longitudinal cracking was greater for sections with good drainage functioning than sections with poor drainage functioning, which suggests that quality of drainage may play a role in the slight differences observed.

Table 38 shows the comparisons of undrained lean concrete base (LCB) versus permeable asphalt-treated base (PATB). Longitudinal cracking was slightly greater in the undrained LCB sections than in the drained PATB sections, but the differences were not found to be significant in any of the cases considered (good drainage functioning, poor drainage functioning, or the two combined). Again, the mean difference in longitudinal cracking was greater for sections with good drainage functioning than sections with poor drainage functioning, which suggests that quality of drainage may play a role in the slight differences observed.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In this study, the potential effects of subsurface drainage on the performance of asphalt and concrete pavements in the SPS-1 and SPS-2 experiments were assessed using available data on IRI for both pavement types, as well as rutting and alligator/longitudinal cracking for asphalt pavements, and faulting, transverse cracking, and longitudinal cracking for concrete pavements.

The results of the preliminary analyses conducted in this study suggest that the SPS-1 and SPS-2 experiments are beginning to manifest differences in some measures of performance that are related to the base type/subdrainage experimental design factor. However, base type and subdrainage presence are confounded in both the SPS-1 and SPS-2 experiments; and it is difficult to differentiate, on the basis of the information that was available for this study, between performance differences due to the presence or absence of subdrainage and performance differences due to base type.

The SPS-1 and SPS-2 experiments suffer from some limitations. First, some cells in the site matrix (i.e., combinations of climate and subgrade type) of each experiment are empty. This is an obstacle to analysis of the SPS-1 and SPS-2 performance data in the manner that was envisioned in the original design of the experiments. Empty cells in an experimental design matrix can be accommodated by using measured data from other cells to estimate values for the missing cells, but only when the factors in the experiment can be considered independent. It is clearly inappropriate to estimate values to fill missing cells when there is reason to believe, a priori, that interactions may exist among the experimental factors.

Second, base type and subdrainage presence are confounded in both the SPS-1 and SPS-2 experiments. It is difficult, perhaps impossible, to separate and quantify the effects of these two factors on the basis of roughness and distress data alone.

Third, discrepancies between the as-designed and as-constructed drainage features appear to exist for many sections. Subdrains were not located and inspected in several SPS-1 and SPS-2 test sections designed to be drained, but were located and inspected in several SPS-1 and SPS-2 sections designed to not be drained. Both types of discrepancies are an obstacle to analysis of the SPS-1 and SPS-2 performance data in the manner that was envisioned in the original experiment design.

The original objectives of NCHRP Project 1-34C were to assess the feasibility of using the SPS1 and SPS-2 data to evaluate the effects of subsurface drainage on pavement performance, to develop an analysis plan, and to identify additional data collection needs. The scope of the study was subsequently expanded to include a preliminary analysis of the SPS-1 and SPS-2 data. This study has demonstrated that appropriate statistical methods can be applied to circumvent the limitations of the incomplete experimental design matrices and the apparent discrepancies in as-designed versus as-constructed drainage features.

The analysis results presented in this report must, however, be considered preliminary, because they are based on data contained in the LTPP database only through mid-June 2001, and because the effects of truck traffic, climate (i.e., different degrees of need for subsurface drainage at different sites), and structural capacity (i.e., different structural contributions of different base types) were not analyzed in depth. In a follow-up study, already underway, more definitive findings are expected to be obtained from analysis of:

- More recent performance data,
- Deflection data (to quantify the structural contributions of different base types),
- Drainage system flow time measurements (to quantify the effectiveness of the drains), and
- Need for drainage as a function of truck traffic level and climate.

Observations from Preliminary Analysis of SPS-1 Performance Data

The preliminary analysis suggests that undrained asphalt pavement sections in the SPS-1 experiment with dense-graded aggregate (AGG) bases may develop roughness, rutting, and cracking more rapidly than drained asphalt-pavement sections with dense asphalt-treated base (ATB) material over permeable ATB material. However, in most cases, the differences detected between the two base types were slight and not statistically significant.

The preliminary analysis suggests that undrained asphalt pavement sections in the SPS-1 experiment with undrained dense-graded asphalt-treated base (ATB) may develop roughness and cracking more slowly than drained permeable asphalt-treated base over aggregate subbase (PATB/AGG), while the undrained sections may develop rutting more rapidly. In no case, however, were the differences detected statistically significant.

The preliminary trends suggest that undrained asphalt pavement sections in the SPS-1 experiment with undrained dense-graded asphalt-treated base over aggregate subbase (ATB/AGG) may develop roughness and rutting more quickly than drained permeable asphalt-treated base over aggregate subbase (PATB/AGG), while the undrained sections may develop cracking more slowly. In no case, however, were the differences detected the statistically significant.

When SPS-1 sections with drainage functioning rated as good were analyzed separately from sections with drainage functioning rated as poor, the results obtained suggest that drainage functioning does play some role in the performance differences observed between drained and undrained sections. In most cases, either a larger positive mean difference or a smaller negative mean difference was calculated for the sections with good drainage functioning. Again, most of the differences detected were not statistically significant.

On the other hand, the preliminary trends suggest that differences in the structural contributions of the different base types may be as important or more important to the performance differences noted between drained and undrained sections. In general, drained permeable asphalt-treated base (PATB) sections have performed slightly better, in some respects, than undrained dense-graded aggregate (AGG) base sections, but slightly worse, in some respects, than undrained dense-graded asphalt-treated base (ATB) sections.

Observations from Preliminary Analysis of SPS-2 Performance Data

The preliminary analysis suggests that undrained concrete pavement sections in the SPS-2 experiment with either an aggregate base (AGG) or a lean concrete base (LCB) may develop roughness, transverse cracking, and longitudinal cracking more rapidly than drained concrete pavement sections with a permeable asphalt-treated base (PATB) and otherwise like design. However, in most cases, the differences detected between the drained and undrained sections were slight and not statistically significant.

The SPS-2 faulting data available through mid-June 2001 were too erratic to support meaningful statistical analysis. This may be largely due to section-wide faulting averages having been calculated from many small-negative, zero, and small-positive faulting measurements. When larger magnitudes of faulting develop—such that the averages are consistently being calculated from positive measurements—trends in faulting with time and traffic may become more evident.

In the analysis of IRI change in drained versus undrained SPS-2 sections, larger mean differences were detected for the PATB sections with drainage functioning subjectively rated as poor than for the PATB sections with drainage functioning rated as good. This was true in comparison to both undrained base types, aggregate and lean concrete. This—to the extent that the subjective ratings of drainage functioning are accurate—suggests that quality of drainage is not a significant factor in the differences observed in IRI increase.

On the other hand, in the analyses of transverse and longitudinal cracking in drained versus undrained SPS-2 sections, larger mean differences were detected for PATB sections with good drainage functioning than for those with poor drainage functioning. This was true in comparison to both undrained base types, aggregate and lean concrete.

RECOMMENDATIONS

Recommendations for Further Monitoring and Analysis of SPS-1 and SPS-2

The subjective assessments of subsurface drainage functioning used in this study should be checked by testing the functioning of the drainage systems. It should be kept in mind that measurement of the permeability of the base material does not shed light on the ability of longitudinal drains and outlets to effectively remove water, nor does visual assessment of the longitudinal drains and outlets shed light on the permeability of the base material. Tests that will take both base permeability and drain/outlet adequacy into consideration are recommended.

Given the confounding of subdrainage presence and base type in the SPS-1 and SPS-2 experiments, deflection data should be analyzed to quantify the relative structural contributions of the different base types used. This information should be used together with the measured drainage flow time data to distinguish, as much as possible, between the effect of base type and the effect of drainage quality in any performance differences observed.

Some inconsistencies exist from site to site with respect to the presence of filter fabric below the permeable asphalt-treated base layer in both the SPS-1 and SPS-2 experiments. Whether or not filter fabric is needed to protect the PATB from infiltration of fines—or whether, for example, a granular subbase serves the same purpose—is a question on which opinion is divided. Ultimately, this question should be resolved by measuring flow times through permeable bases with and without filter fabric protection and analyzing this drainage flow time data together with long-term performance data.

The performance data analyses demonstrated in this study should be repeated with more recent data. By mid-2003, the different SPS-1 sites will have been in service about 5 to 11 years and will have carried between about one and five million flexible pavement ESALs. The different SPS-2 sites will also have been in service about 5 to 11 years and will have carried between about one and fifteen million rigid pavement ESALs.

Subdrains were not located and inspected in 24 percent (26 of 108) of the SPS-1 test sections designed to be drained nor in 14 percent (8 of 56) of the SPS-2 test sections designed to be drained. The presence of subsurface drains and lateral outlets should be confirmed for these test sections. Subdrains were located and inspected in 16 percent (17 of 108) of the SPS-1 test sections designed not to be drained and in 12 percent (14 of 112) of the SPS-2 test sections designed not to be drained. The presence of drains in these sections that should not be drained should be confirmed and must be taken into proper account in future analysis of performance data from the SPS-1 and SPS-2 experiments.

Recommendations for Future Field Experiments to Assess Drainage Effects

The SPS-1 and SPS-2 experiments offer lessons for the design and construction of future field experiments to assess the effects of subsurface drainage on asphalt and concrete pavement performance. One lesson is that the effects of drainage presence and base type should be separated by including in the experimental design both drained and undrained sections of the same base types. Where site conditions are suitable, drainage of the same base type or types via daylighting versus longitudinal edgedrains and outlets is also recommended. Another lesson is that considerable care must be taken in the construction of drainage test sections to ensure that sections designed to be drained have adequate edgedrains and outlets installed and that sections designed not to be drained do not have access to edgedrains and outlets.

Sites selected for future field experiments in subsurface drainage effectiveness should be ones with truck traffic levels sufficiently high to yield clear indications, within ten years, of whether or not subsurface drainage significantly influences pavement performance. Experiments constructed on routes with truck traffic volumes so low that subsurface drainage would not normally be used will not shed much meaningful light on whether or not subsurface drainage does or does not have significant beneficial effects on higher-volume routes.

Uniformity of vertical and horizontal alignments should also be considered in selection of sites for future field experiments in subsurface drainage effectiveness, given that drainage is just one of several factors in the SPS-1 and SPS-2 experiments, the SPS-1 and SPS-2 sites cover considerable lengths, and at some sites, the longitudinal grade varies considerably along the length. Also at some SPS-1 and SPS-2 sites, horizontal alignment changes result in some test sections having an outward transverse grade and being drained toward the outer foreslope (beyond the outer shoulder), with other test sections having an inward transverse grade and being drained to the inner foreslope (under the inner traffic lane and beyond the inner shoulder). In experiments in which the outer traffic lane is the monitored lane, test sections should be located so that the transverse grade and subsurface drainage is consistently outward.

Video inspection of longitudinal edgedrains and their outlets provides some useful information on blockage, sags, and accumulation of water and soil in drains, but does not provide a quantitative measure of the quality of subsurface drainage. Measurement of drainage flow times is recommended for monitoring of future field experiments in subsurface drainage effectiveness. Finally, analysis of drainage flow time data together with deflection data is recommended to differentiate appropriately, and quantitatively, the effects of base type and drainage quality.

REFERENCES

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3. Von Quintus, H. L. and Simpson, A. L., “Initial Evaluation of the SPS-1 Experiment,” LTPP Data Analysis Technical Support Contract, No. DTFH61-96-C-00003, March 2000.
4. Killingsworth, B. and Jordahl, P., “Evaluation of IRI Decreases with Time in the LTPP Southern Region,” Draft Report, Federal Highway Administration Contract No. DTFH61-95-C-00029, September 1996.
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APPENDIXES A AND B

Appendixes A and B as submitted by the research agency are not published herein. For a limited time, they are available from the NCHRP.

Their titles are as follows:

Appendix A: SPS-1 Details
Appendix B: SPS-2 Details

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation