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Significance of "As-Constructed" HMA Air Voids to Pavement Performance from an Analysis of LTPP Data

This digest summarizes key findings from NCHRP Project 20-50(14), "LTPP Data Analysis: Significance of 'As-Constructed' AC Air Voids to Pavement Performance," conducted by Applied Pavement Technology, Inc. It was prepared by Edward T. Harrigan, NCHRP Senior Program Officer, from the contractor's final report authored by Stephen B. Seeds, Applied Pavement Technology, Inc.; R. Gary Hicks, Oregon State University; Gary E. Elkins and Haiping Zhou, LawGIBB PCS; and Todd V. Scholz, Roadworthy Research and Design.

INTRODUCTION

The principal objectives of NCHRP Project 20-50(14), "LTPP Data Analysis: Significance of 'As-Constructed' AC Air Voids to Pavement Performance," were to (1) evaluate the use of long-term pavement performance (LTPP) data for determining the effect of as-constructed air voids on the performance of hot mix asphalt (HMA) pavements, (2) develop new or improved air voids content guidelines for optimum pavement performance, and (3) examine the effect of the level of construction control in the LTPP general pavement studies (GPS) and specific pavement studies (SPS) on the variability of as-constructed air voids. In carrying out these objectives, the research agency mainly relied on LTPP data classified as "Level E" in the LTPP Information Management System (IMS) database and contained in the IMS November 2000 Release 10.9.

In general, accomplishment of these objectives was seriously hampered by a present lack of suitable data in the LTPP database. This digest briefly summarizes the type of data analysis used in support of each objective, describes the results of the analyses, and discusses the limitations of the data. The complete final report of NCHRP Project 20-50(14) is available for loan on request from NCHRP.

Background

Air voids content (AVC), or the amount of voids in a compacted HMA pavement, can have a detrimental effect on the performance of the pavement if it is too high or too low. High AVC increases the likelihood of asphalt stripping, accelerated oxidation, and rapid deterioration. Because of consolidation under wheel loading, high AVC can also contribute to the development of rutting in the wheel paths. Low AVC, however, increases the likelihood of bleeding, shear flow, and permanent deformation (i.e., rutting) in the wheel paths. Accordingly, control of HMA compaction during construction is essential to achieving its maximum performance.

Most highway agencies are using AVC along with other volumetric properties, such as voids in the mineral aggregate (VMA) or voids filled with asphalt (VFA), as measures of quality in their quality control and quality assurance (QC/QA) specifications for HMA. Over the years, these agencies have developed statistical tolerances for AVC from historical data and set specification levels based on experience. Some state DOTs (e.g., Oregon and Washington) have actually used laboratory mix performance data to establish the effect of AVC on pavement performance (Linden et al., 1988; Bell et al., 1984). The findings from these early studies

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suggest, for example, that for every 1-percent drop in AVC, there is a corresponding 10-percent loss of pavement life. Despite the success of some of these studies, developing relationships between AVC and pavement performance has generally proven to be difficult, with no universally accepted standard available to user agencies. The lack of guidelines creates problems for agencies when changes in construction practices, test protocols, and materials lead to changes in AVC or pavement structure. Agency efforts to implement the Superpave mix design procedure (McGennis et al., 1995) have demonstrated this particular problem.

In addition, information comparing as-designed and as-constructed AVC is generally not available in published form. Such comparisons may help quantify the typical range of AVC variability based on normal construction practices. Data from the Federal Highway Administration (FHWA) LTPP program GPS sections and especially from newly constructed and routinely monitored test sections (e.g., LTPP SPS sections), as well as WesTrack and other accelerated pavement test studies, may shed some light on this subject.

Objectives

The primary goal of this project was to examine the significance of as-constructed AVC on HMA pavement performance. To achieve this goal, the following specific objectives were established:

1. Evaluate the use of LTPP data for determining the effect of as-constructed AVC on the performance of HMA pavements.
2. Develop new or improved AVC guidelines for optimum pavement performance.
3. Examine the effect of the level of construction control between the LTPP GPS and SPS sections on the variability of as-constructed AVC.

To satisfy the first objective, available data in the LTPP database were evaluated for the potential to develop prediction models and determine the sensitivity of pavement performance and HMA stiffness to as-constructed AVC. To satisfy the second objective, the results of the sensitivity analyses of LTPP models, along with analyses of other existing models, were analyzed to determine trends and, ultimately, to develop improved AVC guidelines that would help optimize pavement performance. To satisfy the last objective, available data in the LTPP database were evaluated for the potential to estimate the difference in AVC variability between pavement sections constructed with a level of QC/QA associated with typical agency practice (i.e., GPS sections) and pavement sections constructed with a hypothesized higher level (i.e., SPS sections) because of their known experimental nature at the time of construction.

RESEARCH APPROACH

The research was accomplished in the four tasks described in the following sections.

Task 1: Develop Prediction Models for Pavement Performance and HMA Stiffness Using Data Available from the Current FHWA LTPP Program

This purpose of this task, which is fully described in Chapter 2 of the final report, was to develop statistically sound prediction models relating certain measures of pavement performance (i.e., fatigue cracking and permanent deformation or rutting) and HMA stiffness to as-constructed AVC. The LTPP database has the potential to provide a substantial amount of field data that could be used to establish a meaningful connection between pavement performance and AVC. Data from other important field experiments (i.e., WesTrack, Mn/ROAD, FHWA-ALF, Louisiana TRC, and Austroads) were also examined; however, analyses were not conducted with these data for two reasons. In the case of Mn/ROAD, FHWA-ALF, and Louisiana TRC, the experiments were not designed to treat AVC as an independent variable; consequently, there was no basis to evaluate the effects of AVC variability. In the case of WesTrack and Austroads, analyses had already been performed and suitable models were available to evaluate their sensitivity to AVC.

The LTPP database contains thousands of pavement sections and is subdivided according to pavement type, experiment type, and data type. Consequently, before any statistical analyses were performed, four basic steps were conducted to process the raw data into three separate project databases: one for fatigue life, one for rutting life, and one for HMA stiffness. These steps were as follows.

Screening and Section Selection

Candidate pavement sections from throughout the LTPP database were identified primarily on the basis of the availability of HMA test results that could be used to calculate the as-constructed AVC. Other criteria for section selection depended on the type of prediction model. In the case of both fatigue life and rutting life models, past traffic information as well as performance data were needed. In addition, limiting criteria were established on certain pavement structural characteristics to avoid complications brought about by behavioral and performance differences in different pavement combinations. For example, overlaid sections were excluded in the fatigue database because of the likely effect that the original asphalt surface would have on the rate of fatigue crack progression.

Section Classification

All selected sections were classified within a matrix in order to establish the range of inference associated with any developed prediction model. The two primary factors included in the classification were HMA surface thickness and environmental region (based on temperature and moisture).

Calculation of AVC

AVC was calculated for each selected section using a standardized formula and the laboratory test results available in the LTPP database. In this step, it was found that much of the testing had been performed on samples obtained well after initial pavement construction. Accordingly, 18 months after the initial construction was established as a cut-off point, all sections tested beyond that point were eliminated from the project database.

Calculation of Dependent Variable

Values for the dependent variable in the three databases were calculated. In the case of fatigue life and rutting life, failure criteria were established and the number of ESAL applications required to achieve those levels was estimated on the basis of traffic information in the LTPP database. In the case of HMA stiffness, the resilient modulus of the HMA surface was estimated through a process involving back-calculation analysis of nondestructive test data with an adjustment for mix temperature.

After the three databases were completed, statistical regression analyses were planned to produce the desired prediction models that would relate pavement performance and HMA stiffness to as-constructed AVC. Unfortunately, as further described below, graphs of the data for all three models indicated that either no correlation existed or that the derived relationship would not pass the test of engineering reasonableness. Thus, no LTPP-based prediction models were produced.

Task 2: Evaluate the Sensitivity of Pavement Performance and HMA Stiffness to AVC Through the Analysis of Available Relationships

In this task, which is fully described in Chapter 3 of the final report, available information from the literature was used in the absence of models derived from LTPP data to evaluate the sensitivity of pavement performance and HMA stiffness to AVC. This effort required four steps described in the following paragraphs.

Literature Search

An extensive search of the literature was conducted to identify any available prediction models that related pavement performance (in terms of fatigue cracking or permanent deformation) or HMA stiffness to AVC. Initially, the focus of the search was on field performance and as-constructed AVC; however, because of limited past work, the search was expanded to include data from laboratory experiments.

Development of Sensitivity Statistic

The sensitivity of the dependent variable (in this case, performance or HMA stiffness) in a prediction relationship to an independent variable (in this case, AVC) is best represented by the change in the value of the dependent variable as a result of a change in the value of the independent variable. For a linear relationship in which the independent variable appears in only one term, this sensitivity is represented by the coefficient on the independent variable. Graphically, it is depicted by the slope of the line in a graph of the dependent variable versus the independent variable. This approach to characterizing sensitivity was adopted in this study because almost all the prediction models examined either exhibited this simple linear relationship or were adequately represented by it. To provide additional meaning to the sensitivity statistic, the simple linear relationship was mathematically related to a term that has more engineering significance—the percent change in performance (or stiffness) versus the corresponding change in AVC. With this additional feature, one can make statements about the sensitivity of an individual model, such as "the model indicates that a 1-percent increase in AVC will result in a 10-percent decrease in fatigue life."

Develop a Method to Account for Uncertainty

All available measures of the statistical accuracy were calculated and reported in order to provide an indication of the variability or uncertainty associated with the sensitivity of each model. In addition, a rating of the overall reliability of each model was determined. This rating is based on a *subjective* consideration of the quantity and quality of data used to develop the original model, the accuracy of the original fit, and how well the model is represented by the sensitivity statistic.

Determine Sensitivity for Each Prediction Model

Each prediction model was evaluated to determine its sensitivity to AVC and to characterize its uncertainty. The results were summarized in tabular form and then examined as a whole to identify trends and draw conclusions about the overall sensitivity.

Task 3: Examine the Variability in AVC Between Select GPS and SPS Sections from the LTPP Experiment

All SPS sections were constructed after the initiation of the Strategic Highway Research Program (SHRP) LTPP program in the late 1980s. Most of the GPS sections, however, predate the LTPP program. Because the SPS sections were constructed to satisfy certain LTPP experimental design criteria, and because they were constructed with a certain degree of LTPP oversight, it was hypothesized that they would have experienced better quality control and exhibited less variability than their GPS counterparts. Accordingly, the primary purpose of this task, which is more fully described in Chapter 4 of the final report, was to compare the LTPP GPS and SPS data and determine if hypothesized differences in variability did indeed exist. These analyses were performed using standard methods of statistical analysis and several data comparisons.

Task 4: Develop Guidelines for AVC in Construction Specifications

It is widely acknowledged that proper AVC is critical to achieving the maximum performance of an HMA surface layer. The questions remain whether there exist optimum ranges of AVC for performance in terms of fatigue cracking and permanent deformation and to what extent deviations from the target AVC actually affect performance. Therefore, the primary purpose of this task, which is more fully described in Chapter 5 of the final report, was to use the information gathered from the analysis of LTPP data and other sources to suggest improved AVC selection guidelines for use in pavement construction specifications. This purpose was accomplished (to the extent possible) through analysis of findings of the previous three tasks.

ANALYSIS OF LTPP DATA

Overview

This section summarizes the results of analyses of LTPP data to develop prediction models that relate pavement performance and HMA stiffness to AVC. Three separate analyses described further below were conducted to produce models for fatigue cracking, permanent deformation, and HMA stiffness. The section begins with a discussion of the calculation of AVC from LTPP data.

Calculation of AVC

AVC was determined from bulk and maximum specific gravity data in the IMS database. Specifically, AVC was calculated using the following, well-known equation:

$$AVC = 100\left(1 - \frac{G_{mb}}{G_{mm}}\right) \quad (1)$$

where

AVC = air voids content (percent),
G_{mb} = bulk specific gravity of compacted HMA mixture from IMS table TST_AC02, and
G_{mm} = maximum theoretical specific gravity of mixture from IMS table TST_AC03.

For most test sections, several samples were taken for testing of bulk specific gravity, but only one sample was measured for maximum specific gravity. In such cases, the maximum specific gravity was used to compute AVC for all locations of the section where samples were taken for testing of bulk specific gravity.

Fatigue Cracking Analyses

Selection of Test Sections

The IMS November 2000 Release 10.9 of the LTPP IMS database was used for this project. There were 2,522 test sections in the database. To select sections that were most suitable for evaluating the effect of as-constructed AVC on pavement performance in terms of fatigue cracking, the following criteria were applied:

- Pavements have HMA structural layers over granular base;
- Core samples (from which bulk and maximum specific gravity measurements were made) were obtained within 18 months after construction;
- AVC data are available for the bottom of the HMA structural layer; and
- Traffic, pavement structure, and distress survey data are available.

The following LTPP experiments were included for section selection:

- GPS-1, Asphalt Concrete (AC) on Granular Base;
- SPS-1, Strategic Study of Structural Factors for Flexible Pavements;
- SPS-8, Study of Environmental Effects in the Absence of Heavy Loads; and
- SPS-9, Validation of SHRP Asphalt Specifications and Mix Design (Superpave).

As a result of this screening, only the 15 sections shown in Table 1 were potentially useful for further fatigue analysis.

Computation of Total Fatigue

The extent of pavement fatigue for a test section was determined from a combination of fatigue and longitudinal crack data stored in the IMS database. To convert longitudinal cracking in the wheel path to an area, the linear extent was multiplied by 0.15 m (0.5 ft). The following formula was

TABLE 1 Summary of data availability for sections identified for fatigue analyses

State Code	SHRP ID	Experiment Type		Air Voids Data	Monitored Traffic (years)	Fatigue Data (years)
4	0113	SPS	1	-	4	5
4	0114	SPS	1	-	5	5
4	0161	SPS	1	+	5*	4
4	0162	SPS	1	-	5	4
12	0101	SPS	1	+	3	1
12	0102	SPS	1	-	3	2
31	0113	SPS	1	-	2	2
31	0114	SPS	1	-	2	2
35	0101	SPS	1	+	1	3
35	0102	SPS	1	+	1	3
37	1992	GPS	1	+	2	1
39	0101	SPS	1	+	1	1
39	0102	SPS	1	-	1	1
42	1618	GPS	1	+	6	1
48	3835	GPS	1	+	7	5

*Estimated traffic from section 40162.
+ Section has air voids content measured in the laboratory from core samples.
- Section does not have measured air voids content. Data are from adjacent section of the same project.

used to compute the total fatigue area (in square meters) on a test section:

$$\text{Total Fatigue} = \text{AlligatorCrack}(L, M, H) + \text{LongitudinalCrack}(L, M, H) * 0.15 \quad (2)$$

where

AlligatorCrack(L, M, H) = Areal sum (m^2) of measured alligator crack with low, medium, and high severity levels.

LongitudinalCrack(L, M, H) = Linear sum (m) of measured longitudinal crack length in wheel path with low, medium, and high severity levels.

The percentage of fatigue on a test section was determined from the total fatigue divided by the total area of the test section, as shown below:

$$\text{Percent Fatigue} = \text{Total Fatigue}/(\text{Section Length} * \text{Section Width}) \quad (3)$$

LTPP sections are typically 152.4 m (500 ft) long and 3.7 m (12 ft) wide. Thus, 10-percent fatigue would roughly equal 56 m^2 (600 ft^2) of total fatigue within a typical section.

Findings

Because LTPP test sections were constructed at various times, experienced different traffic loading, and exhibited various levels of surface distress, some processing of the data was required to provide a uniform basis for evaluating the effect of as-constructed AVC at the same fatigue cracking level. This processing was accomplished by first determining the equivalent single-axle load (ESAL) applications for all sections reaching 10 percent of fatigue cracking and then developing a relationship between ESAL applications and AVC. Initially, 15 sections were identified for this purpose. However, only five of the sections exhibited noticeable fatigue cracking by the last survey date. Consequently, these five sections were the only ones that could be considered in developing a relationship between ESAL applications and AVC.

Table 2 shows the classification matrix for sections identified for the fatigue analyses by environmental (i.e., climate and moisture) zone and pavement types for various HMA thickness and AVC levels. The environmental zone for each section was determined using the environmental zone map contained in AASHTO's *Guide for Design of Pavement Structures* (AASHTO, 1993).

To estimate the ESAL applications for a test section to reach 10-percent fatigue cracking, a linear regression equation between traffic loading and measured fatigue cracking

TABLE 2 Classification matrix for LTPP sections identified for fatigue-cracking analysis

HMA Thickness (in.)	Air Voids Content (%)	Environmental Zone				Total
		Hot		Freeze		
		Wet	Dry	Wet	Dry	
<4	<5	≤				
	≥5, ≤7	≥		1		1
	>7, ≤9					
	>9					
≥4, ≤6	<5					
	≥5, ≤7		1			1
	>7, ≤9		1			1
	>9					
>6, ≤8	<5					
	≥5, ≤7		1			1
	>7, ≤9					
	>9					
>8	<5	1				1
	≥5, ≤7					
	>7, ≤9					
	>9					
Total		1	3	1	0	5

was developed for the section. The equation was then used to interpolate the ESAL applications for each section for the 10-percent fatigue cracking level.

With estimated ESAL applications and AVC, the basis for a correlation between the two was established. Table 3 shows ESAL applications for all sections reaching the 10-percent fatigue cracking level, while Figure 1 graphically illustrates the relationship.

As can be seen, the data from the five test sections do not provide any indication of a relationship between AVC and fatigue cracking. Although the data shown in Figure 1 suggest that peak performance is obtained with AVC in the 6- to 7-percent range, these results were considered inconclusive and the development of a prediction model was deemed inappropriate for the following reasons:

- Test sections with no fatigue-related cracking were excluded from the analysis; this category included many of the relatively young (i.e., less than 8 years old) LTPP test sections for which as-constructed AVC data were available.
- The fatigue-cracking mechanism is more complicated than a direct relation to compaction expressed in terms of AVC. Other factors affect this relationship, with ESAL applications, pavement structure, and subgrade soil being the most significant.

TABLE 3 Projected ESALs for sections with new HMA exhibiting 10-percent fatigue cracking

State Code	SHRP ID	Experiment Type		HMA Thickness (in.)	Initial Air Voids Content (%)	Projected ESALs (1000)
42	1618	GPS	1	2	5.72	102
35	0102	SPS	1	4.8	6.39	16,129
4	0161	SPS	1	5.7	8.71	1,775
35	0101	SPS	1	7.2	6.82	18,138
48	3835	GPS	1	8.7	4.8	1,737

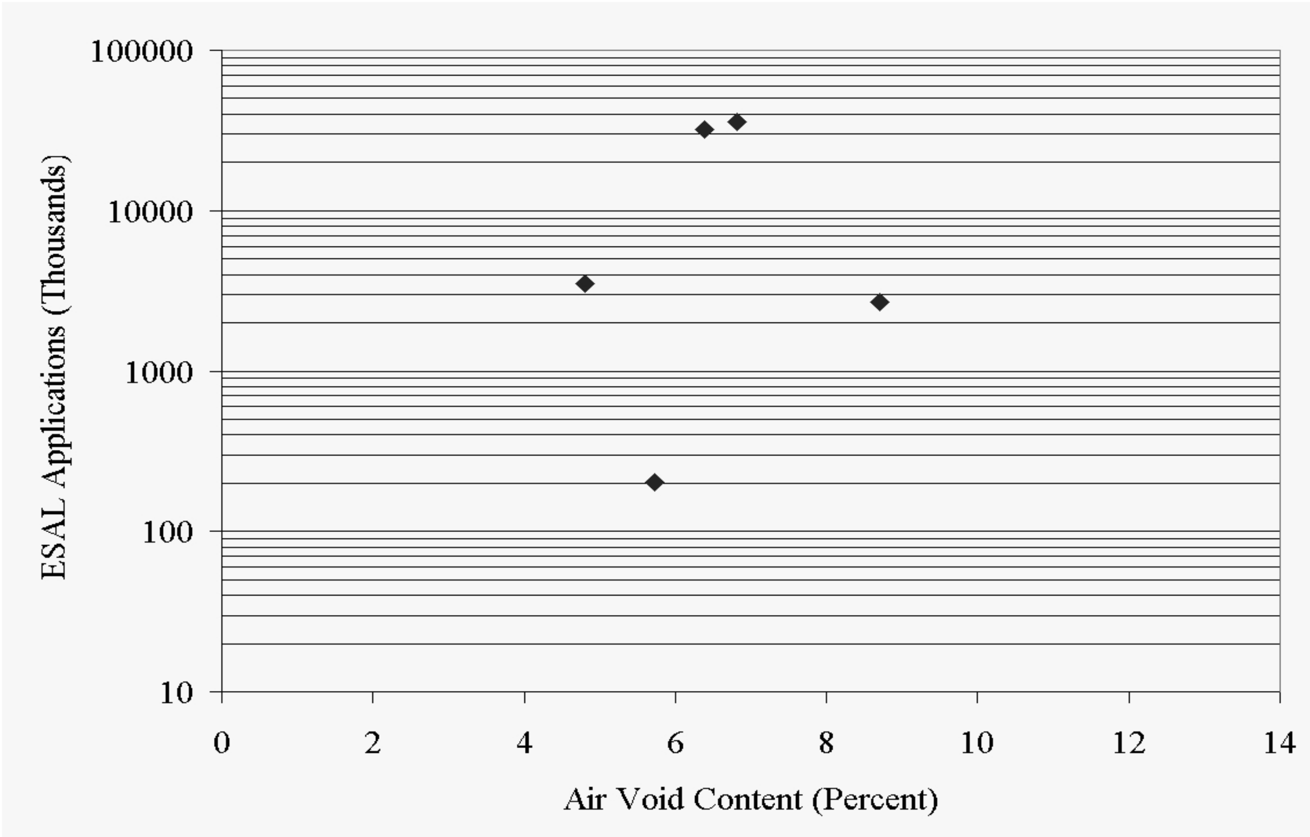

Figure 1. Relationship between estimated ESAL applications and AVC for HMA sections exhibiting 10-percent fatigue cracking.

Permanent Deformation Analyses

Selection of Test Sections

To select sections suitable for evaluating the effect of as-constructed AVC on pavement performance in terms of permanent deformation, the following criteria were applied:

- All types of HMA-surfaced pavement structures are considered;
- Pavement core samples (from which bulk and maximum specific gravity measurements were made) were obtained within 18 months after construction;
- AVC data are available for the uppermost HMA structural layer; and
- Traffic, pavement structure, and rut depth computations from transverse profile data are available.

The following LTPP experiments were included for section selection:

- GPS-1, Asphalt Concrete (AC) on Granular Base;
- GPS-2, AC on Bound Base;
- GPS-6, AC Overlay on AC Pavement, including
  - — 6A—AC Overlay Placed Before LTPP Monitoring,
  - — 6B—Conventional AC Overlay,
  - — 6C—Modified Asphalt AC Overlay,
  - — 6D—Second or Third AC Overlay, and
  - — 6S—AC Overlay with Structural Milling of Existing Surface;
- GPS-7, AC Overlay of Portland Cement Concrete (PCC) Pavement, including
  - — 7A—AC Overlay Placed Before LTPP Monitoring,
  - — 7B—Conventional AC Overlay,
  - — 7C—Modified Asphalt and AC Overlay,
  - — 7D—Second or Third AC Overlay, and
  - — 7S—AC Overlay with Structural Milling of Existing Surface;
- SPS-1, Strategic Study of Structural Factors for Flexible Pavements;
- SPS-5, Rehabilitation of Asphalt Concrete Pavements;
- SPS-6, Rehabilitation of Jointed PCC Pavements;
- SPS-8, Study of Environmental Effects in the Absence of Heavy Loads; and
- SPS-9, Validation of SHRP Asphalt Specifications and Mix Design (Superpave).

After applying these criteria, the 100 sections listed in Table 4 were selected as candidates for the permanent deformation investigation.

TABLE 4 Summary of data availability for sections identified for rutting analyses

State Code	SHRP ID	Experiment Type		Air Voids Content Data	Monitored Traffic (years)	Rut Data (number of measurements)
2	1004	GPS	6B	+	2	5
4	0115	SPS	1	+	5	3
4	0116	SPS	1	+	5	3
4	0117	SPS	1	-	5	3
4	0118	SPS	1	-	5	3
4	0119	SPS	1	-	5	3
4	0120	SPS	1	-	5	3
4	0121	SPS	1	-	5	3
4	0122	SPS	1	+	5	3
4	0123	SPS	1	-	5	3
4	0124	SPS	1	+	5	3
5	3058	GPS	2	+	6	3
6	8534	GPS	6B	+	7	4
6	8535	GPS	6B	+	7	3
8	6002	GPS	6C	+	2	2
9	4020	GPS	7B	+	5	4
17	5151	GPS	7B	+	7	4
24	1634	GPS	6C	+	1*	1
26	0603	SPS	6	+	8	5
26	0604	SPS	6	-	8	5
26	0606	SPS	6	-	8	4
26	0607	SPS	6	-	8	5
26	0608	SPS	6	-	8	5
29	5403	GPS	6B	+	8	5
29	5413	GPS	6B	+	9	4
30	0502	SPS	5	+	5	3
30	0503	SPS	5	-	5	3
30	0504	SPS	5	-	5	3
30	0505	SPS	5	+	5	2
30	0506	SPS	5	-	5	3
30	0507	SPS	5	-	5	3
30	0508	SPS	5	-	5	3
30	0509	SPS	5	-	5	3
30	7066	GPS	6B	+	6	3
30	7076	GPS	6B	+	6	3
30	7088	GPS	6B	+	6	3
31	0115	SPS	1	-	2	3
31	0116	SPS	1	-	2	2
31	0117	SPS	1	-	2	3
31	0118	SPS	1	-	2	2
31	0119	SPS	1	-	2	3
31	0120	SPS	1	+	2	2
31	0121	SPS	1	+	2	3
31	0122	SPS	1	-	2	2
31	0123	SPS	1	-	2	3
31	0124	SPS	1	-	2	3

continued

TABLE 4 Continued

State Code	SHRP ID	Experiment Type		Air Voids Content Data	Monitored Traffic (years)	Rut Data (number of measurements)
34	0502	SPS	5	-	7	5
34	0503	SPS	5	+	7	5
34	0504	SPS	5	+	7	5
34	0505	SPS	5	-	7	5
34	0506	SPS	5	-	7	5
34	0507	SPS	5	+	7	5
34	0508	SPS	5	+	7	5
34	0509	SPS	5	-	7	5
34	0559	SPS	5	+	7	5
35	0103	SPS	1	-	1	2
35	0104	SPS	1	-	1	2
35	0105	SPS	1	+	1	2
35	0106	SPS	1	-	1	2
35	0107	SPS	1	-	1	2
35	0108	SPS	1	-	1	2
35	0109	SPS	1	+	1	2
35	0110	SPS	1	-	1	2
35	0111	SPS	1	+	1	2
35	0112	SPS	1	+	1	1
39	0103	SPS	1	+	1	3
39	0104	SPS	1	-	1	2
39	0105	SPS	1	+	1	3
39	0106	SPS	1	-	1	3
39	0107	SPS	1	-	1	1
39	0108	SPS	1	-	1	3
39	0109	SPS	1	-	1	3
39	0110	SPS	1	-	1	3
39	0111	SPS	1	+	1	2
39	0112	SPS	1	-	1	2
39	0160	SPS	1	-	1	3
39	5010	GPS	7B	+	4	3
40	4086	GPS	6B	+	3	5
40	4161	GPS	2	+	2	5
42	1617	GPS	7B	+	8*	3
42	1618	GPS	6B	+	6	5
42	1691	GPS	7B	+	6	4
48	1119	GPS	6B	+	9	6
48	A502	SPS	5	-	8	5
48	A503	SPS	5	-	8	5
48	A504	SPS	5	-	8	5
48	A505	SPS	5	-	8	5
48	A506	SPS	5	-	8	5
48	A507	SPS	5	-	8	5
48	A508	SPS	5	-	8	5
48	A509	SPS	5	+	8	5
51	1419	GPS	6B	+	7	5
51	1419	GPS	6D	+	2	2
53	1008	GPS	6B	+	4	4

continued

TABLE 4 Continued

State Code	SHRP ID	Experiment Type		Air Voids Content Data	Monitored Traffic (years)	Rut Data (number of measurements)
81	1805	GPS	6B	+	4*	3
83	6450	GPS	6B	+	4	3
83	6451	GPS	6B	+	3	3
89	1125	GPS	6B	+	2	2
90	6410	GPS	6B	+	7	3
90	6412	GPS	6B	+	7	3

* Traffic applications were from estimated information stored in the LTPP database.
+ Section has air voids content measured in the laboratory from core samples.
- Section does not have measured air voids content. Data are from adjacent section of the same project.

Computation of Permanent Deformation

A variety of transverse profile distortion indexes are stored in the LTPP database that can be used to characterize rutting. Quantification of rutting is complex and much more difficult than is apparent to a casual observer. Although LTPP has not yet developed indexes that capture all aspects of rut characterization, relatively simple measures of total rut depth considered in this project were based on (1) a 1.83-m (6-ft) straightedge and (2) a lane-width wire line reference.

In many cases, straightedge and wire line techniques produced identical results; however, in a subset of sections, they did not. The relationship between the straightedge and wire reference depth for the GPS-1 and GPS-2 sections is shown in Figure 2. As is seen, the wire reference depth is always either equal to or greater than the straightedge depth.

For this study, 1.8-m (6-ft) straightedge indices were used since distortions in the transverse profile relative to the wheel path locations and not to the lane edges were of primary interest. These indices should provide the better measure of the HMA mix stability subject to wheel load effects.

Findings

Because LTPP test sections were constructed at various times, experienced different ESAL traffic levels, and exhibited various levels of surface distress, the use of raw measurements of rut depth in the evaluations would be misleading. Instead, the research team decided to express the relationship of AVC to permanent deformation (i.e., rutting performance) in terms of the number of projected ESAL applications to a specified rut depth. This approach requires interpolation

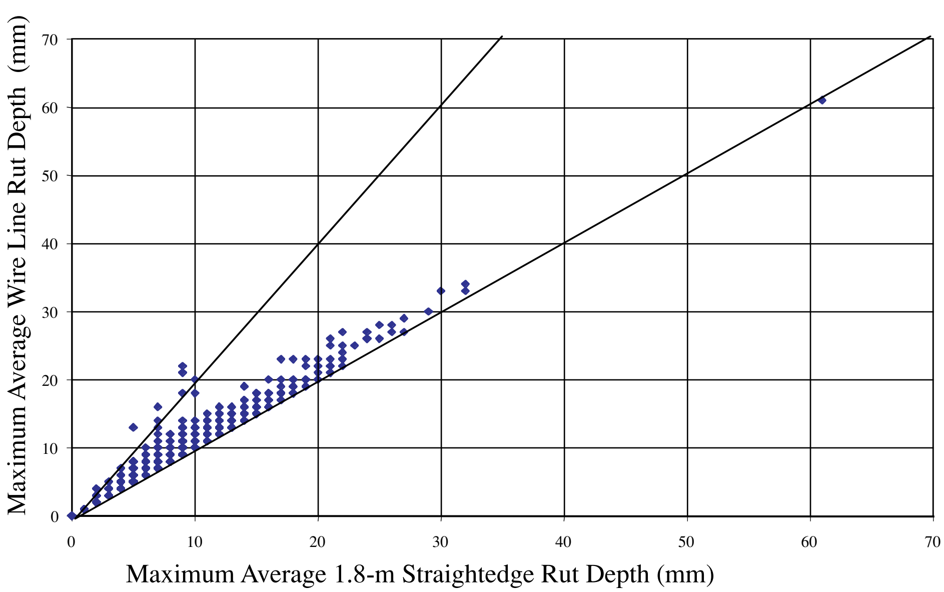

Figure 2. Relationship between straightedge and wire line rut depths for GPS-1 and -2 test sections (lines represent 1:1 and 2:1 ratios).

within or extrapolation of the data. To avoid over-extrapolation, a rut depth of 6 mm (0.25 in.) was selected because of the relatively young age (less than 10 years old) of the LTPP sections for which the necessary data were available.

Initially, 100 sections were identified for this purpose. Further examination of the data indicated that AVC data for many SPS sections were not directly measured or were confounded with those for adjacent sections. After excluding these types of sections, only 51 sections remained.

Table 5 shows the classification matrix for those sections identified for permanent deformation analyses by environmental (i.e., climate and moisture) zone and pavement type for various HMA thicknesses and AVC. The pavement type labeled as COMP (i.e., composite) refers to AC overlays on PCC pavements.

To estimate ESAL applications for each test section reaching a 6-mm (0.25-in.) rut depth, a linear regression equation between ESAL applications and measured rut depth was developed. The equation was then used to estimate ESAL applications for each section based on a 6-mm (0.25-in.) rut depth.

Because of the different pavement type combinations, the analysis of the rutting data was divided into three categories:

- Newly constructed HMA pavements,
- HMA overlays on HMA pavements, and
- HMA overlays on PCC pavements.

The first two categories are classified in Table 5 as HMA, the third as COMP. The findings are discussed in the following sections.

Newly Constructed HMA Pavements. With the estimated ESAL applications and AVC, a correlation was performed between traffic application and AVC. Table 6 presents the ESAL applications to reach 6-mm (0.25-in.) rut depth for the 15 newly constructed HMA sections. Most of these test sections are located on SPS-1 projects with a mixture of base material types.

Figure 3 illustrates the relationship between ESAL applications and AVC. Inexplicably, the relationship suggests better rut performance for mixtures with an in-place AVC of 10 percent, compared with an expected value in the range of 5–8 percent. The test sections with the better rut-resistant mixtures are located in relatively hot regions of Arizona and New Mexico.

HMA Overlays on HMA Pavements. Table 7 presents the estimated ESAL applications to reach a 6-mm (0.25-in.) rut depth for the 30 sections having an HMA overlay on a pre-existing HMA pavement. Most of these test sections are from the GPS-6B experiment, which are HMA mixtures with unmodified binders placed on a HMA surface with no prior cold milling. The two pavement sections in the GPS-6C experiment have overlay mixes with a modified binder. The HMA thickness shown is the total for both the HMA overlay and original HMA layer.

TABLE 5 Classification matrix for LTPP sections identified for rutting analysis

HMA Thickness (in.)	Air Voids Content (%)	Environmental Zone								Total
		Hot				Freeze				
		Wet		Dry		Wet		Dry		
		Pavement Type								
		HMA	Comp	HMA	Comp	HMA	Comp	HMA	Comp	
<4	<5			1			2			3
	≥5, ≤7						1			1
	>7, ≤9									
	>9					1				1
≥4, ≤6	<5			1			2	1		4
	≥5, ≤7			1			1	2		4
	>7, ≤9	1		3				1		5
	>9			1		2				3
>6, ≤8	<5					1		2		3
	≥5, ≤7					1		4		5
	>7, ≤9	1		2		3				6
	>9			1						1
>8	<5	1				7		3		11
	≥5, ≤7	1						1		2
	>7, ≤9	1								1
	>9							1		1
Total		5		10		15	6	15		51

TABLE 6 Estimated ESAL applications to reach a 6-mm (0.25-in.) rut depth for newly constructed HMA sections

State Code	SHRP ID	Experiment Type		HMA Thickness (in.)	Air Voids Content (%)	Projected ESAL (1000)
40	4161	GPS	2	2.8	1.36	63.5
39	0103	SPS	1	3.9	11.17	327.7
39	0105	SPS	1	4	11.8	213.2
39	0111	SPS	1	4	9.76	696.2
4	0116	SPS	1	4.1	9.75	1439.6
4	0122	SPS	1	4.2	10.52	1302.3
31	0120	SPS	1	4.7	5.8	259.0
35	0111	SPS	1	5	7.5	767.4
35	0112	SPS	1	5.1	7.5	750.0
31	0121	SPS	1	5.3	5.8	321.3
35	0105	SPS	1	5.9	7.23	674.8
5	3058	GPS	2	6	7.63	792.0
4	0115	SPS	1	6.6	9.75	2119.7
4	0124	SPS	1	6.7	9.75	1385.4
35	0109	SPS	1	8	7.5	654.9

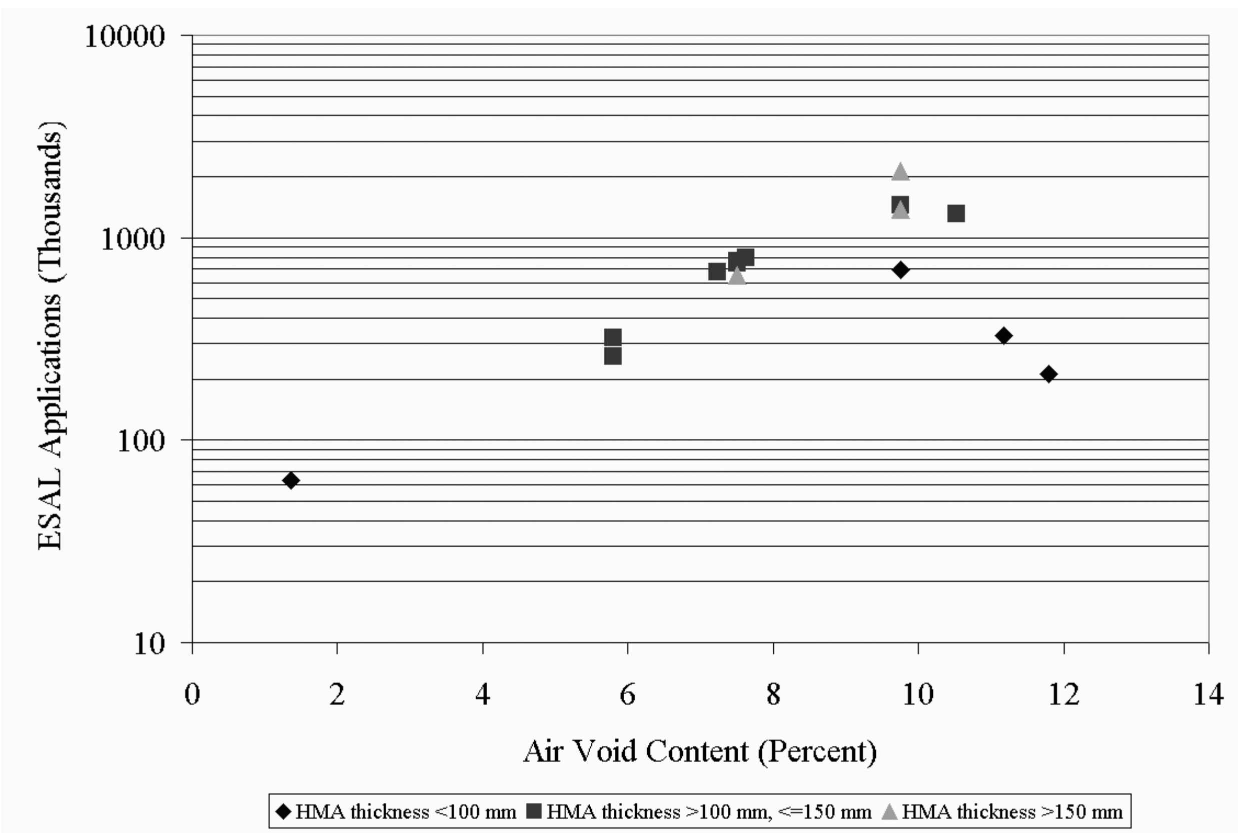

Figure 3. Relationship between estimated ESAL applications to reach 6-mm (0.25-in.) rut depth and AVC for newly constructed HMA pavement sections.

Figure 4 illustrates the relationship between ESAL applications and the AVC of the HMA overlay. As can be seen, there are no discernable trends between AVC and HMA rutting performance. This lack of discernable trends may be due to the presence of different mix types in the data set. However, the lack may also arise from uncertainty in the estimated ESAL applications and the influence of the underlying pavement.

TABLE 7 Estimated ESAL applications to reach 6-mm (0.25-in.) rut depth for HMA overlay sections on HMA pavements

State Code	SHRP ID	Experiment Type		HMA Thickness (in.)	Air Voids Content (%)	Projected ESAL (1000)
2	1004	GPS	6B	5.4	3.97	205.0
40	4086	GPS	6B	5.5	1.56	589.2
53	1008	GPS	6B	5.6	8.33	447.7
29	5403	GPS	6B	6.2	8.89	1497.4
30	7088	GPS	6B	6.6	6.68	1083.6
83	6451	GPS	6B	6.7	5.33	2255.3
24	1634	GPS	6C	6.8	7.71	70.3
30	0505	SPS	5	6.8	3.19	1543.8
29	5413	GPS	6B	6.9	6.97	1328.0
48	1119	GPS	6B	6.9	8.46	319.5
30	0502	SPS	5	6.9	5.62	861.1
30	7066	GPS	6B	7.1	5.61	1072.6
89	1125	GPS	6B	7.1	7.25	456.5
30	7076	GPS	6B	7.6	0.93	213.9
42	1618	GPS	6B	7.9	4.08	134.4
6	8534	GPS	6B	8.2	6.65	1047.1
51	1419	GPS	6B	9.5	4.88	404.2
83	6450	GPS	6B	10.3	4.24	1850.3
6	8535	GPS	6B	10.4	7.65	1889.2
8	6002	GPS	6C	10.5	5.96	206.9
34	0559	SPS	5	11	3.42	2374.2
51	1419	GPS	6D	11.1	4.23	397.9
48	A509	SPS	5	12.1	4.49	804.4
34	0504	SPS	5	13.2	3.86	1970.7
90	6410	GPS	6B	13.6	3.03	443.8
34	0503	SPS	5	13.7	3.8	2729.3
34	0507	SPS	5	14.2	3.75	2249.7
34	0508	SPS	5	14.9	3.86	2594.3
81	1805	GPS	6B	16.3	9.1	1043.0
90	6412	GPS	6B	16.8	2.96	1086.5

HMA Overlays on PCC Pavements. Table 8 shows the estimated ESAL applications to reach a 6-mm (0.25-in.) rut depth for the six sections having an HMA overlay on an existing PCC pavement. Figure 5 illustrates the relationship of rutting performance to AVC.

Although there is an apparent trend for improved rut performance with AVC increasing from 2 to 7 percent, a model developed from so few data points and with such variability would not be statistically meaningful. Furthermore, no observations exist for AVC values above 8 percent, where the rutting trend would likely reverse.

HMA Stiffness Analyses

Selection of Test Sections

Data from all test sections identified for fatigue cracking and permanent deformation analyses were used for evaluating the effect of AVC on HMA stiffness. However, review of the current LTPP database found only a few sections having HMA stiffness information from deflection measurement back-calculation. Thus, to complete this analysis, a simplified back-calculation analysis was performed with the BOUSDEF back-calculation program (Zhou et al., 1990) using the available deflection measurements for each section.

Estimation of HMA Stiffness

Pavement structural data were obtained directly from the LTPP database. During back-calculation, the following simplifications were made:

- Layers with similar materials were combined. (For example, a granular base was combined with a granular subbase.)
- Thin layers directly beneath a thick HMA or PCC layer were treated as a support layer and combined with the next uppermost layer.

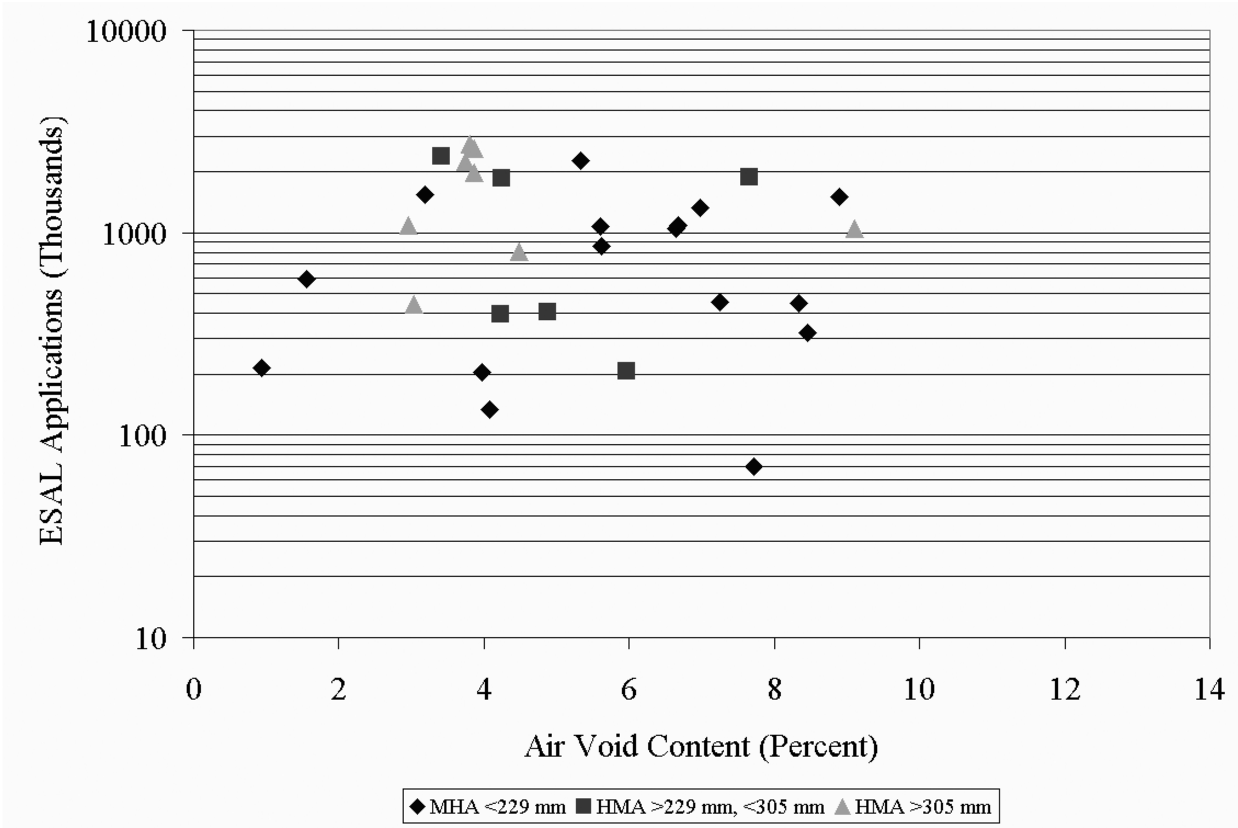

Figure 4. Relationship between estimated ESAL applications and AVC for HMA overlay sections (on existing HMA pavements) exhibiting 6-mm (0.25-in.) rut depth.

TABLE 8 Estimated ESAL applications for HMA overlaid sections on existing PCC pavements reaching a 6-mm (0.25-in.) rut depth

State Code	SHRP ID	Experiment Type		HMA Thickness (in.)	Air Voids Content (%)	Projected ESAL (1000)
9	4020	GPS	7B	3.4	6.97	1093.2
17	5151	GPS	7B	3.3	4.29	7805.3
26	0603	SPS	6	5.1	1.79	2012.6
39	5010	GPS	7B	2.8	3.16	570.2
42	1617	GPS	7B	4.7	6.8	9362.6
42	1691	GPS	7B	4	2.09	443.6

- Typical Poisson's ratios for the various layer materials were used.

To correlate HMA modulus with AVC at the same temperature, the back-calculated HMA moduli for each section were averaged and adjusted to 20°C (68°F) using the following equation (Lukanen et al., 2000):

$$\text{ATAF} = 10^{\text{slope}*(T_r - T_m)} \quad (4)$$

where

ATAF = Asphalt temperature adjustment factor,
slope = Slope of the log modulus versus temperature equation (–0.0195 for the wheel path and –0.021 for midlane are recommended),
T_r = Reference middepth HMA temperature (°C), and
T_m = Middepth HMA temperature at time of measurement (°C).

The estimated modulus at 20°C was then obtained by multiplying the unadjusted modulus by ATAF.

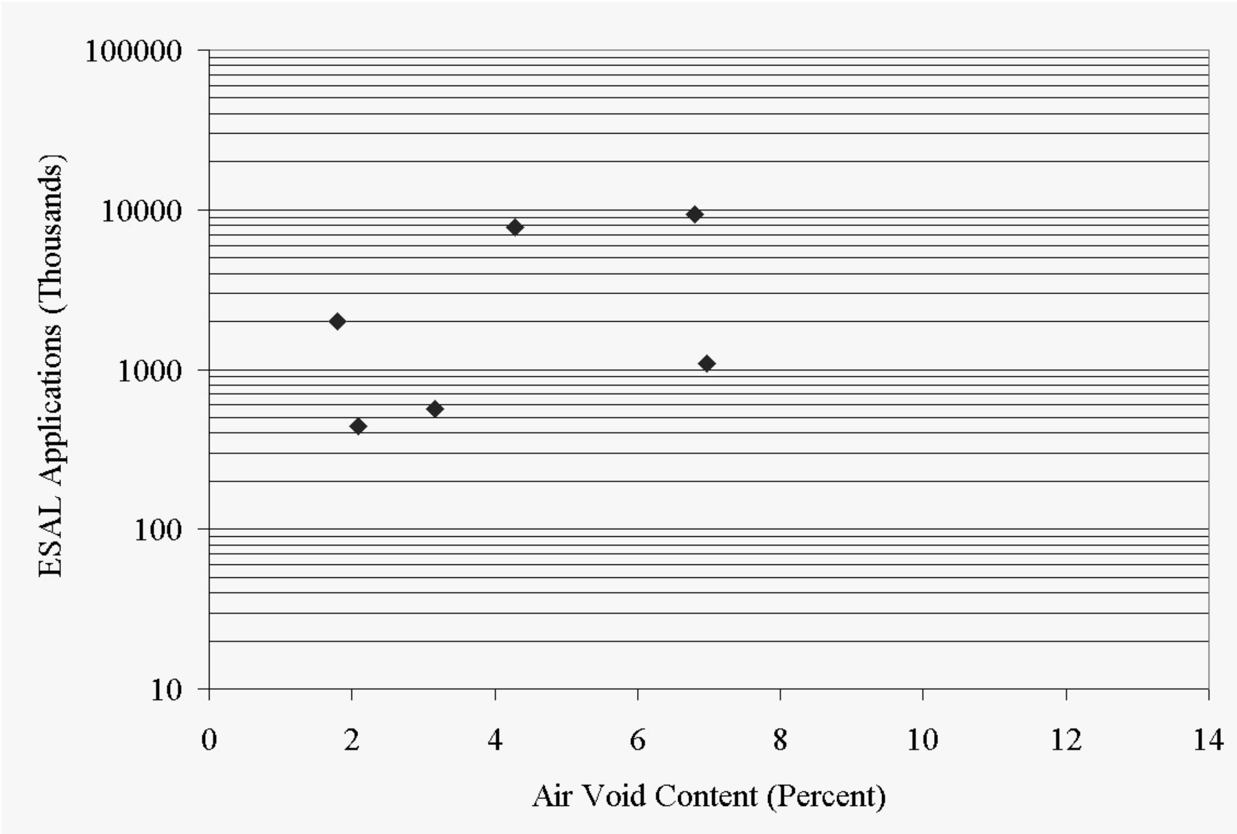

Figure 5. Relationship between estimated ESAL applications and AVC for HMA overlay sections (on existing PCC pavements) exhibiting 6-mm (0.25-in.) rut depth.

For this project, measured surface temperatures, rather than middepth HMA temperatures, were used for correction purposes. The middepth HMA temperature is preferred; however, the effort required to estimate this temperature from other inputs—such as exact timing of the deflection test, the depth for predicting the asphalt temperature, and average air temperature for 5 days prior to deflection test—made the use of the middepth HMA temperature prohibitive. Furthermore, measured surface temperature has often been used in pavement design projects as a first-order approximation.

Findings

Initially, 56 sections were available for analysis (5 for fatigue cracking and 51 for permanent deformation). However, for 6 sections, either there were no deflection data or the back-calculation program did not yield a solution from a measured deflection basin. As a result, only 50 sections were included in the remaining analyses.

Table 9 shows the classification matrix for sections identified for stiffness analyses by environmental (i.e., climatic and moisture) zone and pavement type for various HMA thicknesses and AVC.

The HMA layer moduli were first back-calculated for all the selected LTPP sections from the raw deflection data. Figure 6 illustrates the general correlation between the back-calculated HMA layer modulus and the measured pavement surface temperature during testing. The high and low limits of the back-calculated moduli are shown for each data point. Considering the fact that a multitude of mix types is represented, this graph indicates that a strong relationship between HMA modulus and temperature does exist.

Because HMA stiffness is temperature sensitive, one must separate out its effect if an accurate assessment of the sensitivity of HMA stiffness to as-constructed AVC is to be conducted. As already described, a standard temperature of 20°C (68°F) was chosen as a basis for correction. The relationship between modulus and temperature developed using data from the LTPP database by other researchers (see Equation 4) was used for adjustment purposes.

Table 10 presents the AVC versus HMA layer stiffness (adjusted to the 20°C temperature), while Figure 7 graphically illustrates their relationship. Figure 7 indicates that

TABLE 9 Classification matrix for LTPP sections identified for stiffness analysis

HMA Thickness (in.)	Air Voids Content (%)	Environmental Zone								Total
		Hot				Freeze				
		Wet		Dry		Wet		Dry		
		Pavement Type								
		HMA	Comp	HMA	Comp	HMA	Comp	HMA	Comp	
<4	<5			1			2			3
	≥5, ≤7					1	1			2
	>7, ≤9									
	>9									
≥4, ≤6	<5			1			1			2
	≥5, ≤7			2			1	2		5
	>7, ≤9	1		4					1	6
	>9			1						1
>6, ≤8	<5	1							2	3
	≥5, ≤7			1					4	5
	>7, ≤9	1		2			3			6
	>9			1						1
>8	<5	2					7		3	12
	≥5, ≤7	1							1	2
	>7, ≤9	1								1
	>9								1	1
Total		7		13		1	15	2	12	50

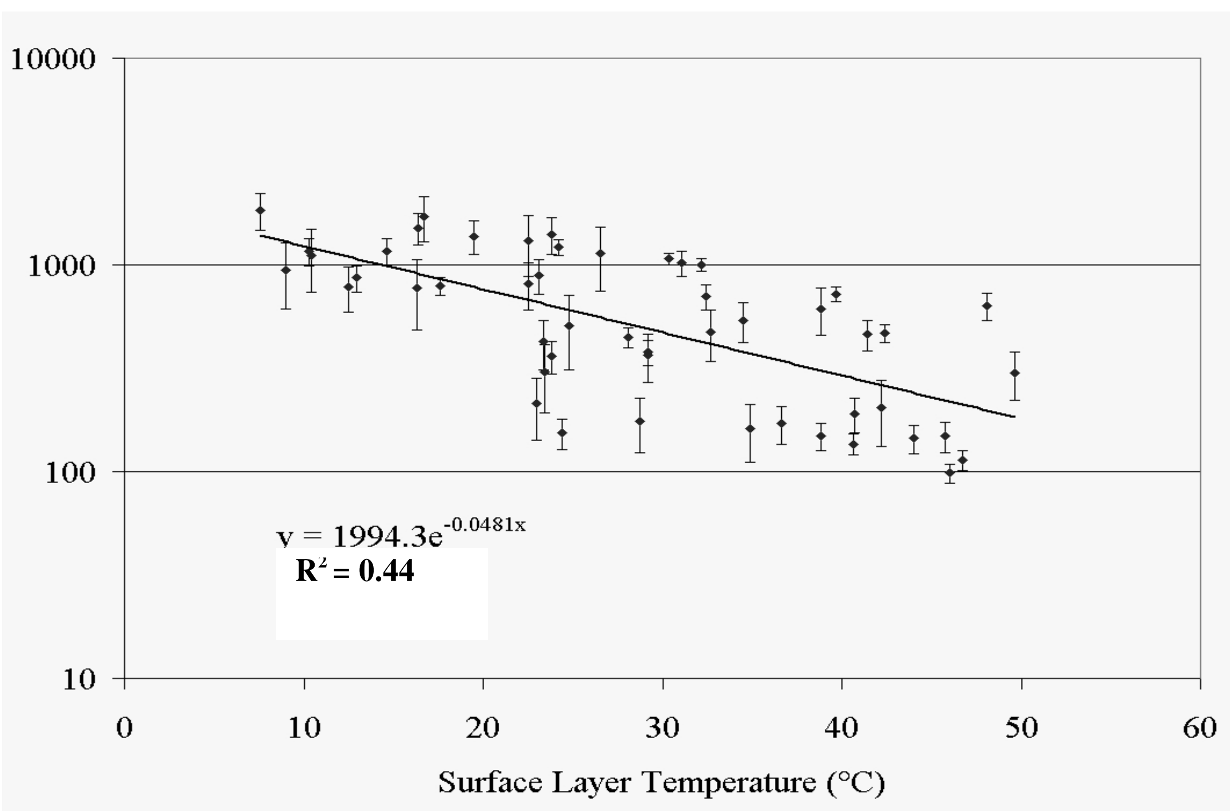

Figure 6. Relationship between HMA modulus versus pavement surface temperature for the selected LTPP sections.

TABLE 10 HMA layer stiffness adjusted to 20°C standard temperature

State Code	SHRP ID	Experiment Type		HMA Thickness (in)	Air Voids Content (%)	Modulus Adjusted to 20°C (1000 psi)
37	1992	GPS	1	2.4	5.27	1,675.2
40	4161	GPS	2	2.8	1.36	259.4
39	5010	GPS	7B	2.8	3.16	361.3
17	5151	GPS	7B	3.3	4.29	653.4
9	4020	GPS	7B	3.4	6.97	494.3
42	1691	GPS	7B	4	2.09	633.0
4	0116	SPS	1	4.1	9.75	725.1
4	0122	SPS	1	4.2	10.52	558.8
31	0120	SPS	1	4.7	5.8	243.2
42	1617	GPS	7B	4.7	6.8	1477.4
35	0102	SPS	1	4.8	6.39	1031.8
35	0111	SPS	1	5	7.5	376.8
35	0112	SPS	1	5.1	7.5	315.9
31	0121	SPS	1	5.3	5.8	314.2
40	4086	GPS	6B	5.5	1.56	836.8
53	1008	GPS	6B	5.6	8.33	1746.4
4	0161	SPS	1	5.7	8.71	574.9
35	0105	SPS	1	5.9	7.23	424.8
5	3058	GPS	2	6	7.63	2237.5
29	5403	GPS	6B	6.2	8.89	1459.4
30	7088	GPS	6B	6.6	6.68	1527.8
4	0115	SPS	1	6.6	9.75	1051.0
83	6451	GPS	6B	6.7	5.33	711.2
4	0124	SPS	1	6.7	9.75	1470.8
30	0505	SPS	5	6.8	3.19	551.6
12	0101	SPS	1	6.8	4.98	1706.9
24	1634	GPS	6C	6.8	7.71	640.7
30	0502	SPS	5	6.9	5.62	352.4
48	1119	GPS	6B	6.9	8.46	555.3
30	7066	GPS	6B	7.1	5.61	1674.9
89	1125	GPS	6B	7.1	7.25	429.3
35	0101	SPS	1	7.2	6.82	573.1
30	7076	GPS	6B	7.6	0.93	1024.1
35	0109	SPS	1	8	7.5	482.0
6	8534	GPS	6B	8.2	6.65	1280.4
48	3835	GPS	1	8.7	4.8	1223.9
51	1419	GPS	6B	9.5	4.88	911.1
83	6450	GPS	6B	10.3	4.24	629.7
6	8535	GPS	6B	10.4	7.65	1734.8
8	6002	GPS	6C	10.5	5.96	471.1
34	0559	SPS	5	11	3.42	1136.9
51	1419	GPS	6D	11.1	4.23	1430.2
48	A509	SPS	5	12.1	4.49	1346.8
34	0504	SPS	5	13.2	3.86	1209.9
90	6410	GPS	6B	13.6	3.03	187.3
34	0503	SPS	5	13.7	3.8	915.8
34	0507	SPS	5	14.2	3.75	752.4
34	0508	SPS	5	14.9	3.86	1285.2
81	1805	GPS	6B	16.3	9.1	343.1
90	6412	GPS	6B	16.8	2.96	348.4

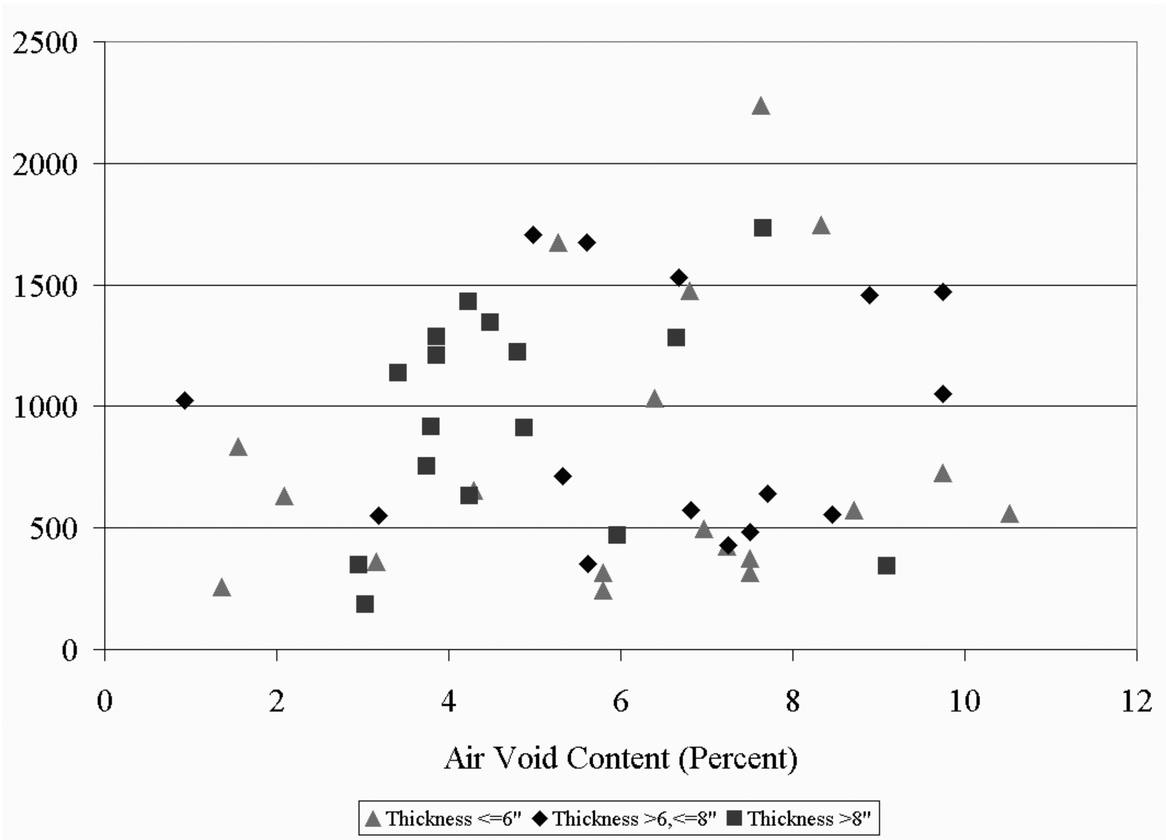

Figure 7. Relationship between HMA layer stiffness (at 20°C) and AVC.

there is a slight tendency for the HMA stiffness (i.e., elastic modulus) to increase with increasing AVC; however, the relationship is not statistically significant and no prediction model could be developed.

Summary

This section summarizes the results of analyses of LTPP data for the purpose of developing prediction models that relate fatigue performance, rut performance, and HMA stiffness to as-constructed AVC:

1. Fatigue cracking: Because of the limited number of pavement sections (five) that satisfied the selection criteria and the scatter of the data, no relationship between fatigue performance and AVC could be established.
2. Rutting: Rutting performance was evaluated for three principal pavement types in the LTPP database.

   - The analysis of data from newly constructed HMA pavements showed unreasonable results (i.e., an optimum AVC of about 10 percent). However, only a limited number of pavement sections (15) satisfied the selection criteria.
   - The analysis of data from HMA overlays on pre-existing HMA pavements produced no apparent sensitivity and no correlation. In this case, the 30 sections that satisfied the selection criteria exhibited wide scatter.
   - The analysis of data from HMA overlays on pre-existing PCC pavements showed a possible trend of improved rut performance in an AVC range of 2–7 percent. However, only six sections satisfied the criteria and there was considerable data scatter.

   Other factors that likely contributed to the variability of the results include (1) a limited range of AVC in some of the data, (2) uncertainty in the calculated AVC and estimated ESAL applications, and (3) unquantified variability in the underlying support conditions.
3. HMA Stiffness: Fifty pavement sections were identified, processed, and evaluated in an effort to develop a relationship between HMA stiffness and as-constructed AVC. The findings basically indicated that there is no apparent relationship between HMA stiffness and AVC. Although uncertainty exists in the estimation of HMA stiffness and AVC, the number of data points and the fact that a wide variety of pavements was represented suggest that this result is meaningful.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main conclusions of this study are presented below in terms of how well the study results satisfied the three objectives of the project.

Objective 1—Evaluate the Use of LTPP Data for Determining the Effect of As-Constructed AVC on the Performance of HMA Pavements

1. Fatigue cracking—It was not possible to develop a fatigue-cracking model based on LTPP data that characterize the effect of as-constructed AVC. There is a lack of data from which to calculate as-constructed AVC; also, many sections do not exhibit significant cracking.
2. Permanent deformation—Data for three different pavement types in the LTPP database were analyzed in an attempt to develop models that characterize the effect of as-constructed AVC on rutting. For the model based on data from newly constructed HMA pavements, the limited amount of data suggested an optimum AVC of about 10 percent, well outside the range of engineering reasonableness. For the model based on data from HMA overlays on preexisting HMA pavements, the limited data indicated that AVC had no effect on rutting performance. For the model based on data from HMA overlays on PCC pavements, the data were insufficient for analysis. Thus, it was concluded that the available LTPP data cannot support the development of valid prediction models for rutting.
3. HMA stiffness—Processing of the LTPP data for HMA stiffness yielded 50 pavement sections that could potentially be used to develop a prediction model for HMA stiffness as a function of AVC. Analysis of the data, however, indicated that no relationship existed. Because of the apparent validity of the approach and the quantity of data, it was concluded that the inherent variability of the results was too large to detect what are likely minor trends.

Objective 2—Develop New or Improved AVC Guidelines for Optimum Pavement Performance

Because no models could be developed from the available LTPP data to relate as-constructed AVC with fatigue cracking and rutting, it was not possible to develop compaction guidelines for HMA pavement construction without relying on other data sources in the literature. According to these other data sources, the target range for AVC to minimize the future development of both fatigue cracking and rutting is 5–6 percent. Thus, the recommended target compaction level is 94–95 percent of maximum density. More detailed discussion of the basis of these guidelines is presented in Chapter 3 of the final report.

Objective 3—Examine the Effect of the Level of Construction Control Between the LTPP GPS and SPS Sections on the Variability of As-Constructed AVC

According to a multifaceted analysis of available data in the LTPP database, no significant difference exists between the variability of AVC in the GPS and SPS sections. This finding suggests that the better quality control hypothesized for the SPS sections (if the better quality control did indeed exist) had no effect on the variability of AVC and is supported by the following observations:

1. In the overall comparison of the GPS sections with those in the SPS, the standard deviations of AVC were 1.42 and 1.05 percent, respectively.
2. For comparisons between "like" experiments in the GPS and SPS sections, the standard deviation of AVC of the SPS sections was greater in 11 out of the 14 cases than the standard deviation of the corresponding GPS sections. In six of these instances, the difference in standard deviations was statistically significant.
3. For comparisons between GPS and SPS sections grouped by HMA thickness, the standard deviation of AVC of the SPS sections was greater in 11 out of the 14 cases than the standard deviation of the corresponding GPS sections. In 9 of these 14 cases, the difference in standard deviations was statistically significant.

Recommendations

1. Given the nature of the LTPP database and the limited amount of information that can be used to calculate as-constructed AVC on a true section-by-section basis, it is recommended that any future analyses involving the consideration of as-constructed AVC be postponed until such time as more data become available. It is recommended that these analyses be achieved by developing a valid statistical experiment design, identifying target LTPP sections, and then obtaining cores from these sections for the purpose of determining their in-situ AVC. To obtain the best estimate of the "as-constructed" AVC, the cores should be obtained from areas outside the wheel paths that have received the least trafficking and densification.
2. In the process of evaluating the relationship between HMA stiffness and AVC in the LTPP database, a relatively simple approach was used to derive a relationship to account for the effect of pavement temperature. This approach is described in Chapter 2 of the final report for NCHRP Project 20-50(14). Despite the simplicity of the approach and the use of an approximate method of HMA stiffness back-calculation, the model showed a good correlation between stiffness and pavement temperature. A more rigorous analysis of the LTPP database should be carried out to develop a model to predict HMA stiffness as a function of pavement temperature, age of the HMA, and other mix characteristics.

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